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# INITIAL FLUID INJECTION CHARACTERISTICS PRE-CAMBRIAN INTERVAL PRESSURE INJECTION DISPOSAL WELL ROCKY MOUNTAIN ARSENAL DENVER, COLORADO

Prepared for
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Signed and Sealed E. A. Pulumbus

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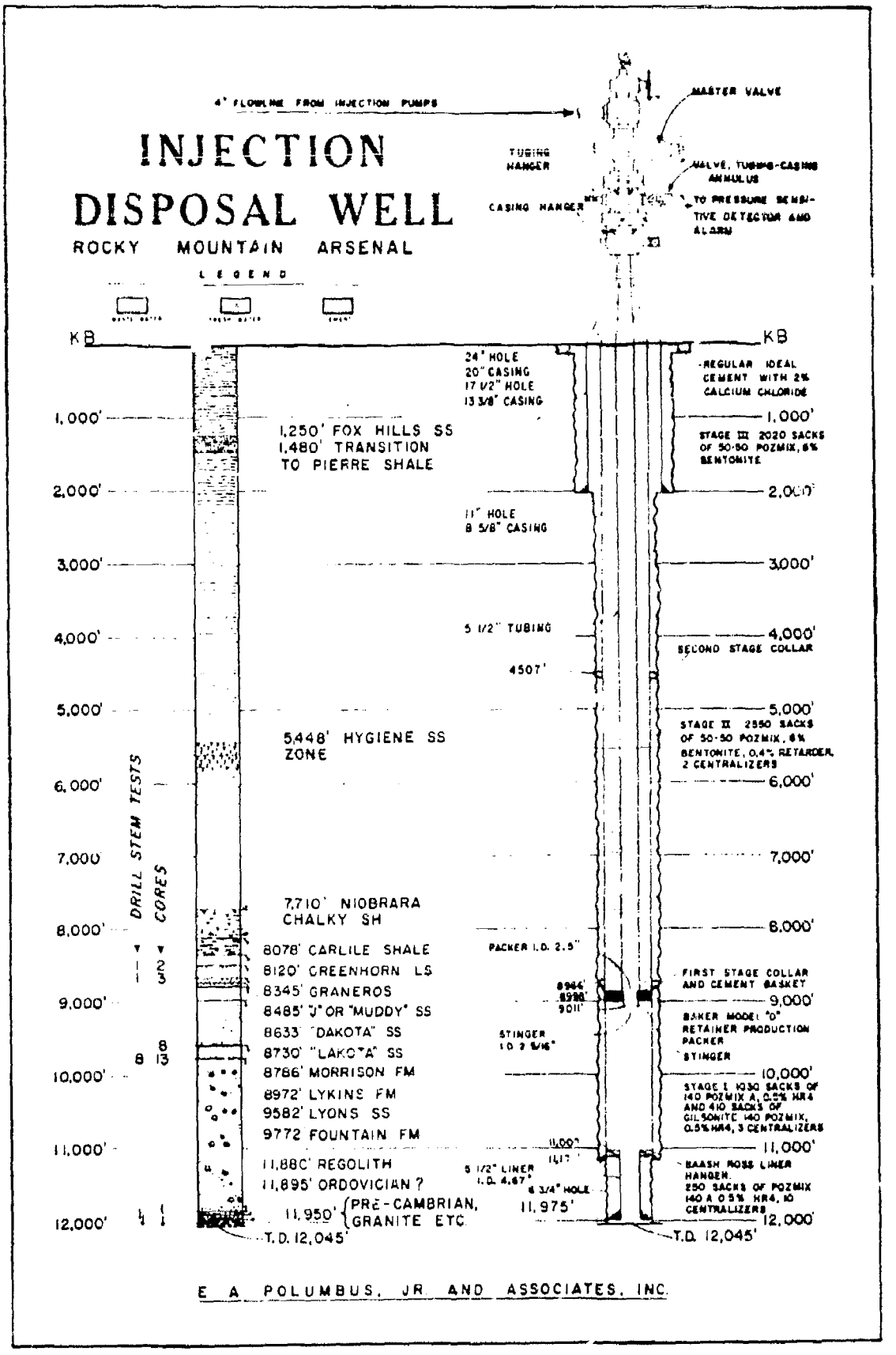


E A POLUMBUS, JR AND ASSOCIATES, INC.

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## INTRODUCTION

The accumulating waste effluent from chemical plants at the Rocky Mountain Arsenal, Denver, Colorado presented the problem of finding a permanent solution for disposal in such a manner as to protect shallow fresh water aquifers from contamination. The Chemical Corps of the United States Army considered various methods for handling these waste fluids and decided upon the drilling of a deep pressure injection disposal well in the search for a subsurface formation reservoir capable of accepting fluid at rates up to 800 gallons per minute under a maximum of 2,000 psi surface injection pressure for a number of years.

The site selected for the well on the Arsenal grounds was near storage Pond F in Section 26, Township 2 South, Range 67 West, Adams County, Colorado. The responsibility for designing and drilling the well was vested in the Department of the Army, U. S. Army Engineer District, Omaha, Corps of Engineers. The petroleum engineering consulting firm of E. A. Polumbus, Jr., and Associates, Inc., was engaged to design the drilling program, manage the drilling and testing, provide engineering and geological services, and conduct the initial injection tests.

Reference to the following two reports prepared by Polumbus and Associates will provide adequate background details concerning the design and drilling of the injection well:

"Final Design Analysis, Pressure Injection Disposal Well, Rocky Mountain Arsenal (July 5, 1960)"

"Final Report on Drilling, Rocky Mountain Arsenal Pressure Injection Disposal Well (November 30, 1961)"

The latter report presents the drilling history and details of the formation evaluation program followed in the disposal well which was spudded March 10, 1961 and penetrated into Pre-Cambrian granite to a final total depth of 12,045 feet.

Prior to drilling the injection well eight zones were considered to offer potentialities as injection reservoirs. These consisted of the Hygiene, Codel, "J", Dakota, and Lakota sandstones, the Morrison, Lyons and Fountain formations. Two of these now appear to offer potential injection reservoirs; namely, fractured intervals of the Lyons and Fountain formations. Additionally, the Pre-Cambrian granite hornblende gneiss (Figure 3) containing fractures within the interval 11,975 to 12,045 feet constituted an initially unsuspected potential injection reservoir. The core No. 28 (Table 14), drill stem test Nos. 13 and 14 (Tables 1 and 2 and Figure 2), and the behavior of lost circulation encountered while penetrating this section indicated a zone of sufficient merit to warrant completing the well with 5 1/2-inch liner cemented at 11,975 feet (Figure 1) and proceeding first to evaluate this open hole interval for an injection reservoir.

This report, "Initial Fluid Injection Characteristics, Pre-Cambrian Interval, Rocky Mountain Arsenal Pressure Injection Disposal Well,"

constitutes a sequel to the Final Report on Drilling. It presents the results of initial injection tests using City of Denver potable water to evaluate the Pre-Cambrian interval 11,975 feet to total depth 12,045 feet for an injection reservoir.

## OBJECTIVES OF INITIAL INJECTION TESTS

Predictions of injection performance may be made on zones of interest by conducting drill stem tests as drilling proceeds and without the necessity of completing the well. From the results of these tests, decisions may be made whether or not to conduct further tests. In the Rocky Mountain Arsenal Disposal well, every effort was extended to thoroughly examine promising zones whenever conditions were permissible. Such a zone exists in the Pre-Cambrian interval 11,975 to 12,045 feet wherein the fractured granite encountered caused considerable drilling fluid to be lost to the formation.

Before attempts are made to inject disposal fluid into a formation, it is prudent first to examine various reservoir parameters which will be useful in diagnosing problems that may arise during continuous injection operations. The important parameters are as follows:

1. Reservoir capacity to accept fluid.
2. Drainage radius.
3. Total reservoir pore volume.
4. Reservoir pressure and temperature.
5. Well damage or skin effect.
6. Compatibility of injection fluid with reservoir fluid and matrix material.

Numerous techniques may be employed in evaluating these properties, all of which were utilized in the Rocky Mountain Arsenal well whenever conditions permitted.

Ordinary means of volumetric computations are impractical for two important reasons. First, horizontal limits of the reservoir are unknown. Second, fracture porosity evidently accounts for a substantial portion of the total void space. The results of the tests conducted to date give strong evidence that the "effective" reservoir is expanding as injection continues, but it is impractical to attempt to identify the drainage radius or effective reservoir volume, because the necessary parameters cannot be accurately defined at this time.

Additional injection tests with potable water are considered unnecessary, and injection of treated Pond F water is now recommended. It is advisable to continue to conduct periodic pressure fall-off tests as proposed herein for the purpose of better defining the parameters mentioned above.

Included in the testing program was a determination of friction factors of the tubing string under various flowing rates. These factors are required in subsequent calculations of reservoir performance where pressure losses due to friction are significant.

## RESULTS OF INITIAL INJECTION TESTS

Injection tests included in the study incorporate considerations of mud losses into the formation while drilling and completing, brief injection tests with potable water through 4 1/2-inch drill pipe while the rig was on location and injection tests with City of Denver water through 5 1/2-inch tubing using surface plant pumping facilities. The results of all tests are shown graphically in Figure 12, which relates rates of injection to wellhead injection pressures. It may be noted that in the reservoir conditions that existed during the time of these initial injection tests, a definite relationship exists which can be extrapolated to indicate an injection rate of 800 gallons per minute at a wellhead pressure of approximately 865 psig.

The chronology of tests conducted on the initial injection interval is presented graphically in Fig 4. Details of individual tests are presented graphically in Figures 5, , and 8 to 11. In Figure 4, values of reservoir pressure and cumulative differential volume injected or removed from the formation are plotted as a function of time. The summary of calculations of important pressure tests are also included in this figure. It may be pointed out that the results of each test were evaluated and utilized in making a decision on subsequent test procedures. Because of the complex nature of the Pre-Cambrian interval tested, dependable results were not always obtainable.

Introduced into the equations from which calculation of injectivity characteristics were made are certain physical constants for which measured values are unobtainable. In such cases, it was necessary to use assumed values for expediency in completing the calculations. It is believed that computations for all parameters are reasonable except possibly drainage radius. Nevertheless, calculations of drainage radius are significant in that it appears to be increasing with volume injected. This feature is not entirely unexpected in view of the prevailing fracture system, and it may very well prove to be a valuable asset in fulfilling the initial objectives of the disposal well.

The values of various physical constants used in evaluating pressure tests are as follows:

| | | |
|---|---|---|
| Datum depth ($Z_d$) | 12,000 | ft |
| Temperature at 12,000 ft ($T_f$) | 240 | $^oF$ |
| Viscosity of water at 240°F ($\mu$) | 0.28 | cp |
| Compressibility of water ($C_w$) | $3 \times 10^{-7}$/ | psi |
| Effective compressibility ($Cw_e$) | $8.8 \times 10^{-6}$/ | psi |
| Porosity (Fractures only) ($\phi$) | 3.0 | % |
| Density formation water ($\rho_{fw}$) | 1.05 | gm/cc |
| Density fresh water ($\rho_w$) | 1.00 | gm/cc |
| Density drilling fluid ($\rho_m$) | 1.08 | gm/cc |
| Density muddy water ($\rho_{mw}$) | 1.06 | gm/cc |

The tabulation of results of each pressure test conducted in this interval are included in Tables 1 through 12 excluding Table 8. The

calculated values of important parameters for all tests are summarized in Table 13. In addition to the symbols given previously, the following definitions of symbols apply to Table 13.

| | |
|---|---|
| $\triangle V$ | Barrels fluid injected or withdrawn. |
| $\Sigma \triangle V$ | Cumulative differential volume. |
| Fluid | Fluid in hole during pressure test. |
| $\rho$ fluid | Density of fluid. |
| $Z_b$ | Position of pressure bomb. |
| $Z_d - Z_b$ | Distance between bomb depth and datum. |
| $\triangle P_{cor}$ | Pressure correction = 0.433 ($\rho$ fluid) $(Z_d - Z_b)$. |
| $P_s$ | Static pressure at 12,000 ft. |
| P* | Extrapolated pressure at 12,000 ft. |
| $P_m$ | Maximum or minimum pressure at 12,000 ft. |
| Kh | Formation capacity in millidarcy-feet. |
| F.E. | Flowing efficiency (accounts for well damage) |
| $r_e$ | Apparent drainage radius in ft. |

An attempt was made to secure a representative formation fluid sample in order to determine compatibility and other characteristics of this fluid. Because of the loss of drilling fluid into the fractures during drilling and coring, it was very questionable whether either drill stem test No. 13 or 14 provided uncontaminated formation fluid samples. The best sample analyzed indicated a chloride content of 46,400 ppm.

Normally it is possible to produce a well for a short time to clean out the contaminated fluid and then secure a bottom-hole sample which should very nearly reflect true formation fluid characteristics. Initial

injection tests through the drill pipe, while the rig was still on location, indicated that the interval below 11,975 feet would accept fluid at sufficient rates to warrant further investigation. Before the drilling rig was moved efforts were made to obtain a formation fluid sample through 4 1/2 inch drill pipe by air lift which is a high capacity lifting method. This proved to be uneconomical because of the low rate of fluid entry. Upon removal of the rig from the location, rods, tubing and pump were run as a more economical means of obtaining the desired sample. Figure 7 presents graphically the chloride content of the produced fluid as a function of cumulative volume withdrawn.

After several days of pumping the well pumped down, and the recovery became so small that continuance of the effort to gain a representative sample was unwarranted. It should be noted that after producing 1,100 barrels fluid in excess of the injected volume, the chloride content was considerably lower than that obtained from the drill stem test No. 14. The significance of this behavior is that either a limited reservoir volume is implied, or during production the fractures possibly were being squeezed together by compression forces which resulted in restricting fluid entry into the wellbore. This factor supports the suggestion given above that the effective reservoir is expanding when the pressure is restored by injection and may continue to do so during the continuous injection period to follow. The composite graph (Figure 12) showing

injection rates versus injection pressures for all injection tests in the Pre-Cambrian interval 11,975 feet to 12,045 feet lends support to this interpretation.

## CONCLUSIONS

1. The rates, with corresponding injection pressures at which the Pre-Cambrian interval (11,975 to 12,045 feet) accepted fluid during tests, are shown graphically on Figure 12. Extrapolation of the rate vs. pressure trend indicates an injection pressure of approximately 865 psig at an injection rate of 800 gallons per minute. The maximum actual injection rate through 5 1/2-inch tubing with available surface plant facilities was 400 gallons per minute at 650 psig wellhead pressure with no observed pressure rise during test.
2. The reservoir consists of fractures which apparently expand as additional volumes of fluid are injected.
3. Extension of effective reservoir boundaries is indicated for the period of testing discussed herein.
4. Continued injection of fluid and the contemporaneous recording of pressure and injected volume data, plus periodic pressure fall-off tests are essential to a more positive evaluation of the Pre-Cambrian reservoir.

## RECOMMENDATIONS CONCERNING THE CONTINUOUS INJECTION PERIOD

1. It is recommended that the following data be collected for each day of injection operations.
   a. Injection Rate
   b. Daily Injected Volume
   c. Tubing Pressure
   d. Annulus Pressure
   e. Solids content and chemical characteristics of injected fluid
2. Periodic observations of tubing pressure should be made throughout the day during the initial injection period. Significant increases should be studied without delay as related to reservoir performance. If the tubing pressure reaches 2,000 psi, the injection rate should be reduced.
3. During the first 90 days of operation, a 24-hour fall-off test is recommended at the end of each 30-day period. Every effort should be exercised to maintain a constant injection rate for approximately 10 days prior to shutting in the well for these tests.
4. Future test requirements should be evaluated after examining the results of the 30-day fall-off tests.
5. A water storage pressure chamber should be connected to the 8 5/8-ingh - 5 1/2-inch annulus to provide for variations in the annular volume requirements due to subsurface temperature variations as influenced by well operations.

6. Corrosion test coupons should be placed in the injection stream as near the wellhead as possible in order to evaluate the severity of corrosion in the water injection path. Some oilfield operators consider the upper limit of corrosive activity to be 1.0 MPY (0.001 inches per year) for subsurface conditions. This however requires individual economic analysis involving casing design specifications, cost of replacement, cost of corrosion inhibition, possible irreparable reservoir damage due to the end products of corrosion, and damage to the permanent installation in the wellbore.

It should be mentioned that coupons do not necessarily evaluate the entire injection path. Before extensive or costly corrosion inhibition programs are initiated based upon coupon tests alone, additional corroboration should be obtained from other sources; such as caliper surveys in the 5 1/2-inch tubing, periodic visual inspection of the casing head, pumps and other surface appurtenances.

Table 1

# ROCKY MOUNTAIN ARSENAL
# PRESSURE INJECTION DISPOSAL WELL
# DRILL STEM TEST NO. 13

September 5, 1961

| Time Minutes | Shut-in Pressure, psi At 9,645 Feet | Time Minutes | Shut-in Pressure, psi At 9,645 Feet |
|---|---|---|---|
| 0 | 2,565 | 50 | 3,732 |
| 1 | 2,981 | 54 | 3,732 |
| 2 | 3,111 | 58 | 3,732 |
| 3 | 3,211 | 62 | 3,732 |
| 4 | 3,274 | 66 | 3,732 |
| 5 | 3,335 | 70 | 3,732 |
| 6 | 3,393 | 74 | 3,732 |
| 7 | 3,436 | 78 | 3,732 |
| 8 | 3,477 | 82 | 3,732 |
| 9 | 3,515 | 86 | 3,732 |
| 10 | 3,548 | 90 | 3,732 |
| 14 | 3,634 | 94 | 3,732 |
| 18 | 3,673 | 98 | 3,732 |
| 22 | 3,692 | 102 | 3,732 |
| 26 | 3,703 | 106 | 3,732 |
| 30 | 3,712 | 110 | 3,732 |
| 34 | 3,719 | 114 | 3,732 |
| 38 | 3,727 | 118 | 3,732 |
| 42 | 3,727 | 122 | 3,732 |
| 46 | 3,732 | | |

| | |
|---|---|
| Formation | Early Paleozoic |
| Interval Tested | 9,660-11,985 |
| Flow Periods | 3 and 60 minutes |
| Closed-in Times | 30 and 122 minutes |
| Gauge Depth | 9,645 |
| Initial Flow Pressure | 856-1,117 |
| Initial Shut-in Pressure | 3,868 |
| Final Flow Pressure | 925-2,565 |
| Final Shut-in Pressure | 3,732 |
| Recovery | 5,330 feet mud (no water cushion) |

Table 2

# ROCKY MOUNTAIN ARSENAL
# PRESSURE INJECTION DISPOSAL WELL
# DRILL STEM TEST NO. 14

September 6, 1961

| Time Minutes | Shut-in Pressure, psi At 11,007 Feet |
|---|---|
| 0 | 3,508 |
| 9.3 | 3,782 |
| 18.6 | 3,910 |
| 27.9 | 4,000 |
| 37.2 | 5,059 |
| 46.5 | 4,093 |
| 55.8 | 4,116 |
| 65.1 | 4,129 |
| 74.4 | 4,138 |
| 83.7 | 4,148 |
| 93.0 | 4,155 |

| | |
|---|---|
| Formation | Early Paleozoic |
| Interval Tested | 11,020-11,985 |
| Flow Periods | 6 and 156 minutes |
| Closed-in Times | none and 93 minutes |
| Gauge Depth | 11,007 feet |
| Initial Flow Pressure | 1,684-1,844 |
| Initial Shut-in Pressure | none (bypassed and reopened) |
| Final Flow Pressure | 1,692-3,508 |
| Final Shut-in Pressure | 5,155 |
| Recovery | 2,000 feet water cushion<br>5,400 feet salt water |

Table 3

ROCKY MOUNTAIN ARSENAL
PRESSURE INJECTION DISPOSAL WELL NO. 1
INJECTION AND FALL-OFF TESTS

TEST NO. I (September 20, 1961)

| Time | Surface Pressure | Pressure at 11,975' K.B. | Remarks |
|---|---|---|---|
| 0 min. -45 min. | 975 psi | 6170 psi | Injected 16,200 gallons at 385 GPM. |
| 45 min. - 0 sec. | 850 | 6045 | Instantaneous shut-in pressure. |
| 45 min. -10 sec. | 825 | 6020 | Shut-in 10 sec. |
| 45 min. -20 sec. | 525 | 5720 | Shut-in 20 sec. |
| 45 min. -30 sec. | 250 | 5445 | Shut-in 30 sec. |
| 45 min. -40 sec. | 225 | 5420 | Shut-in 40 sec. |
| 45 min. -50 sec. | 220 | 5415 | Shut-in 50 sec. |
| 45 min. -60 sec. | 210 | 5405 | Shut-in 60 sec. |
| 46 min. -10 sec. | 205 | 5400 | Shut-in 70 sec. |
| 46 min. -40 sec. | 190 | 5385 | Shut-in 100 sec. |
| 47 min. -10 sec. | 175 | 5370 | Shut-in 130 sec. |
| 47 min. -40 sec. | 125 | 5320 | Shut-in 160 sec. |
| 48 min. -10 sec. | 125 | 5320 | Shut-in 190 sec. |
| 48 min. -40 sec. | 110 | 5305 | Shut-in 220 sec. |
| 49 min. -10 sec. | 110 | 5305 | Shut-in 250 sec. |
| 53 min. - 0 sec. | 75 | 5270 | Shut-in 480 sec. |
| 56 min. - 0 sec. | 50 | 5245 | Shut-in 660 sec. |
| 58 min. - 0 sec. | 0 | 5195 | Shut-in 780 sec. |

Injection test through 10,700 feet of 4 1/2-inch drill pipe.
5 1/2-inch liner set at 11,975 feet.
Injection interval 11,975-12,045 feet.

Table 4

ROCKY MOUNTAIN ARSENAL
PRESSURE INJECTION DISPOSAL WELL NO. 1
INJECTION AND FALL-OFF TESTS

TEST NO. II (September 20, 1961)

| Time | Surface Pressure | Pressure at 11,975' K.B. | Remarks |
|---|---|---|---|
| 0 min. - 5 min. | 250 psi | 5445 psi | Injected 1008 gallons at 216 GPM |
| 5 min. - 0 sec. | 250 | 5445 | Instantaneous shut-in pressure |
| 5 min. -10 sec. | 175 | 5370 | Shut-in 10 sec. |
| 5 min. -20 sec. | 90 | 5285 | Shut-in 20 sec. |
| 5 min. -30 sec. | 25 | 5220 | Shut-in 30 sec. |
| 5 min. -40 sec. | 0 | 5195 | Shut-in 40 sec. |

Injection test through 10,700 feet of 4 1/2-inch drill pipe.
5 1/2-inch liner set at 11,975 feet.
Injection interval 11,975-12,045 feet.

Table 5

ROCKY MOUNTAIN ARSENAL
PRESSURE INJECTION DISPOSAL WELL NO. 1
INJECTION AND FALL-OFF TESTS

TEST NO. III (September 20, 1961)

| Time | Surface Pressure | Pressure at 11,975' KB | Remarks |
|---|---|---|---|
| 0 min. -15 min. | 1475 psi | 6670 psi | Injected 8232 gallons at 538 GPM |
| 15 min. - 0 sec. | 1475 | 6670 | Instantaneous shut-in pressure |
| 15 min. -10 sec. | 225 | 5420 | Shut-in 10 sec. |
| 15 min. -20 sec. | 225 | 5420 | Shut-in 20 sec. |
| 15 min. -30 sec. | 210 | 5405 | Shut-in 30 sec. |
| 15 min. -40 sec. | 190 | 5385 | Shut-in 40 sec. |
| 15 min. -50 sec. | 175 | 5370 | Shut-in 50 sec. |
| 16 min. - 0 sec. | 160 | 5355 | Shut-in 60 sec. |
| 16 min. -30 sec. | 110 | 5305 | Shut-in 90 sec. |
| 17 min. - 0 sec. | 100 | 5295 | Shut-in 120 sec. |
| 17 min. -30 sec. | 80 | 5275 | Shut-in 150 sec. |
| 18 min. - 0 sec. | 75 | 5270 | Shut-in 180 sec. |
| 18 min. -30 sec. | 50 | 5245 | Shut-in 210 sec. |
| 20 min. - 0 sec. | 0 | 5195 | Shut-in 300 sec. |

Injection test through 10,700 feet of 4 1/2-inch drill pipe.
5 1/2-inch liner set at 11,975 feet.
Injection interval 11,975-12,045 feet.

Table 6

ROCKY MOUNTAIN ARSENAL
PRESSURE INJECTION DISPOSAL WELL NO. 1
INJECTION AND FALL-OFF TESTS

TEST NO. IV (September 20, 1961)

| Time, min. | Surface Pressure | Pressure at 6,000' K.B. | Pressure at 11,975' K.B. | Remarks |
|---|---|---|---|---|
| 0-136 | 700 psi | 3182 psi | 5775 psi | Injected 20,916 at average rate of 250 GPM |
| 137 | 200 | | | Shut-in 1 min. |
| 146 | 100 | 2864 | 5457 | Shut-in 10 min. |
| 156 | 0 | 2713 | 5306 | Shut-in 20 min. |
| 176 | | 2652 | 5245 | Shut-in 40 min. |
| 196 | | 2618 | 5211 | Shut-in 60 min. |
| 216 | | 2592 | 5185 | Shut-in 80 min. |
| 236 | | 2577 | 5170 | Shut-in 100 min. |
| 256 | | 2551 | 5144 | Shut-in 120 min. |
| 276 | | 2543 | 5136 | Shut-in 140 min. |
| 296 | | 2524 | 5117 | Shut-in 160 min. |
| 316 | | 2515 | 5108 | Shut-in 180 min. |
| 336 | | 2506 | 5099 | Shut-in 200 min. |
| 356 | | 2498 | 5091 | Shut-in 220 min. |
| 376 | | 2491 | 5084 | Shut-in 240 min. |
| 531 | | 2432 | 5025 | Shut-in 395 min. |
| 546 | | 2432 | 5025 | Shut-in 410 min. |
| 561 | | 2428 | 5021 | Shut-in 425 min. |
| 639 | | 2413 | 5006 | Shut-in 503 min. |

Injection test through 10,700 feet of 4 1/2-inch drill pipe.
5 1/2-inch liner set at 11,975 feet.
Injection interval 11,975-12,045 feet.

Table 7

ROCKY MOUNTAIN ARSENAL
PRESSURE INJECTION DISPOSAL WELL NO. 1
INJECTION AND FALL-OFF TESTS

TEST NO. V (September 20-21, 1961)

| Time, min. | Surface Pressure, psi | Pressure at 5,000', psi | Pressure at 11,975', psi | Remarks |
|---|---|---|---|---|
| 0 | 1120 | 2991 | 6018 | Begin injection at 263 GPM |
| 2 | 1120 | 2991 | 6018 | " " |
| 30 | 1120 | 2991 | 6018 | " " |
| 60 | 1120 | 2991 | 6018 | " " |
| 120 | 1120 | 2991 | 6018 | " " |
| 142 | 1120 | 2991 | 6018 | Stop injection after 37,346 gallons |
| 144 | | 2807 | 5834 | Shut-in 2 min. |
| 152 | | 2783 | 5810 | Shut-in 10 min. |
| 162 | | 2525 | 5552 | Shut-in 20 min. |
| 172 | | 2390 | 5417 | Shut-in 30 min. |
| 182 | | 2287 | 5314 | Shut-in 40 min. |
| 202 | | 2202 | 5229 | Shut-in 60 min. |
| 262 | | 2143 | 5170 | Shut-in 120 min. |
| 322 | | 2116 | 5143 | Shut-in 180 min. |
| 382 | | 2105 | 5132 | Shut-in 240 min. |
| 442 | | 2090 | 5117 | Shut-in 300 min. |
| 502 | | 2084 | 5111 | Shut-in 360 min. |
| 562 | | 2073 | 5100 | Shut-in 420 min. |
| 682 | | 2052 | 5077 | Shut-in 540 min. |
| 802 | | 2027 | 5054 | Shut-in 660 min. |

Injection test through 10,700 feet of 4 1/2-inch drill pipe.
5 1/2-inch liner set at 11,975 feet.
Injection interval 11,975-12,045 feet.

Table 8

ROCKY MOUNTAIN ARSENAL
PRESSURE INJECTION DISPOSAL WELL
PRE-CAMBRIAN INTERVAL, 11,975 TO 12,045'
CUMULATIVE WATER PRODUCED BY AIR LIFTING AND PUMPING
VERSUS CHLORIDE CONTENT OF WATER SAMPLE

| Cumulative Production Barrels | Chloride Content ppm | Cumulative Production Barrels | Chloride Content ppm |
|---|---|---|---|
| 650 | 1,600 | 4,453 | 33,500 |
| 2,035 | 4,000 | 4,465 | 28,400 |
| 2,090 | 13,000 | 4,483 | 24,600 |
| 2,517 | 13,000 | 4,530 | 27,000 |
| 2,624 | 12,000 | 4,670 | 26,000 |
| 2,966 | 15,000 | 4,699 | 27,000 |
| 3,330 | 15,000 | 4,744 | 26,000 |
| 3,580 | 18,000 | 4,790 | 31,000 |
| 3,920 | 26,000 | 4,870 | 32,500 |
| 3,975 | 25,000 | 4,896 | 31,500 |
| 4,011 | 21,000 | 4,920 | 32,000 |
| 4,200 | 28,000 | 4,934 | 31,000 |
| 4,211 | 32,000 | 4,956 | 33,000 |
| 4,321 | 29,500 | 4,982 | 31,250 |
| 4,417 | 33,500 | 5,001 | 32,500 |

Table 9

ROCKY MOUNTAIN ARSENAL
PRESSURE INJECTION DISPOSAL WELL
INJECTIVITY TESTS THROUGH 5 1/2-INCH TUBING
PRE-CAMBRIAN INTERVAL 11,975-12,045'

TEST NO. 1
January 3, 1962

| Shut-in Time | Wellhead Pressure, psi |
|---|---|
| 0 | 280 |
| 10 Seconds | 120 |
| 20 Seconds | 110 |
| 30 Seconds | 105 |
| 40 Seconds | 95 |
| 50 Seconds | 95 |
| 60 Seconds | 92 |
| 2 Minutes | 75 |
| 3 Minutes | 62 |
| 4 Minutes | 54 |
| 5 Minutes | 48 |
| 6 Minutes | 42 |
| 7 Minutes | 35 |
| 8 Minutes | 29 |
| 9 Minutes | 25 |
| 10 Minutes | 21 |
| 11 Minutes | 17 |
| 12 Minutes | 13 |
| 13 Minutes | 9 |
| 14 Minutes | 6 |
| 15 Minutes | 3 |
| 16 Minutes | 0 |

| | |
|---|---|
| Effective Injection Time | 856 minutes |
| Average Injection Rate | 206 GPM |
| Volume of Denver City Water Injected | 4,200 barrels |

The bottom-hole pressure was not recorded since the clock in the Amerada pressure bomb malfunctioned.

Table 10

ROCKY MOUNTAIN ARSENAL
PRESSURE INJECTION DISPOSAL WELL
INJECTIVITY TESTS THROUGH 5 1/2-INCH TUBING
PRE-CAMBRIAN INTERVAL 11,975-12,045'

TEST NO. 2
January 5, 1962

| Shut-in Time Minutes | Wellhead Pressure psi | Pressure At 3,000' psi | Shut-in Time Minutes | Wellhead Pressure psi | Pressure At 3,000' psi |
|---|---|---|---|---|---|
| 0 | 335 | 1,630 | 480 | 29 | 1,347 |
| 1 | 190 | | 540 | 25 | 1,340 |
| 5 | 138 | | 600 | 20 | 1,339 |
| 10 | 112 | | 840 | 12 | 1,322 |
| 15 | 102 | 1,401 | 1080 | 9 | 1,314 |
| 30 | 87 | 1,388 | 1,235 | line drained | 1,306 |
| 45 | 80 | 1,386 | 1,295 | | 1,305 |
| 60 | 76 | 1,383 | 1,355 | | 1,303 |
| 75 | 72 | 1,381 | 1,415 | | 1,301 |
| 90 | 68 | 1,378 | 1,475 | | 1,300 |
| 120 | 64 | 1,371 | 1,535 | | 1,293 |
| 150 | 60 | 1,370 | 1,595 | | 1,290 |
| 180 | 56 | 1,370 | 1,655 | | 1,288 |
| 210 | 52 | 1,370 | 1,715 | | 1,287 |
| 240 | 48 | 1,368 | 1,820 | | 1,285 |
| 300 | 43 | 1,363 | 1,880 | | 1,282 |
| 360 | 39 | 1,353 | 1,940 | | 1,279 |
| 420 | 34 | 1,352 | | | |

| | |
|---|---|
| Effective Injection Time | 682 minutes |
| Average Injection Rate | 208 GPM |
| Volume of Denver City Water Injected | 3,380 barrels |

The bottom-hole pressure was not recorded since the Amerada pressure bomb was dropped in the hole when the wire line broke at 9,000 feet.

Table 11

ROCKY MOUNTAIN ARSENAL
PRESSURE INJECTION DISPOSAL WELL
INJECTIVITY TESTS THROUGH 5 1/2-INCH TUBING
PRE-CAMBRIAN INTERVAL 11,975-12,045'

TEST NO. 3
January 22, 1962

| Shut-in Time | Wellhead Pressure psi | Pressure at 7500' psi |
|---|---|---|
| 0 | 535 | 3,666 |
| 1 min. | 335 | 3,596 |
| 5 min. | 270 | |
| 10 min. | 245 | |
| 15 min. | 232 | |
| 30 min. | 210 | 3,437 |
| 1 hr. | 202 | 3,416 |
| 2 hrs. | | 3,391 |
| 2 hrs. 30 min. | | 3,388 |
| 3 hrs. | | 3,385 |
| 4 hrs. | | 3,382 |
| 6 hrs. | | 3,354 |
| 8 hrs. 30 min. | | 3,353 |
| 9 hrs. | | 3,290 |
| 12 hrs. | | 3,211 |
| 15 hrs. | | 3,186 |
| 18 hrs. | | 3,174 |
| 20 hrs. | | 3,171 |
| 26 hrs. | | 3,164 |
| 30 hrs. | | 3,161 |
| 36 hrs. | | 3,158 |

Effective Injection Time 424 min.
Injection Rates
10 min. at 104 GPM
10 min. at 208 GPM
324 min. at 312 GPM
80 min. at 416 GPM

Volume of Denver City Water Injected 3,450 bbls.

The Amerada pressure bomb was set at 7,500' for safety precautions.

Table 12

ROCKY MOUNTAIN ARSENAL
PRESSURE INJECTION DISPOSAL WELL
INJECTIVITY TESTS THROUGH 5 1/2-INCH TUBING
PRE-CAMBRIAN INTERVAL 11,975-12,045'

TEST NO. 4
January 25, 1962

| Shut-in Time | Wellhead Pressure psi | Pressure At 8,000' psi | Shut-in Time | Wellhead Pressure psi | Pressure At 8,000' psi |
|---|---|---|---|---|---|
| 0 | 630 | 3,997 | 16 hrs. | 160 | 3,642 |
| 1 min. | 380 | 3,884 | 18 hrs. | 150 | 3,633 |
| 5 min. | 335 | | 20 hrs. | 141 | 3,627 |
| 15 min. | 290 | | 22 hrs. | 132 | 3,618 |
| 30 min. | 260 | 3,755 | 24 hrs. | 123 | 3,608 |
| 1 hr. | 240 | 3,725 | 26 hrs. | 115 | 3,605 |
| 2 hrs. | 230 | 3,712 | 28 hrs. | 107 | 3,602 |
| 4 hrs. | 220 | 3,691 | 30 hrs. | 99 | 3,599 |
| 6 hrs. | 210 | 3,688 | 32 hrs. | 91 | 3,587 |
| 8 hrs. | 200 | 3,682 | 34 hrs. | 83 | 3,587 |
| 10 hrs. | 190 | 3,666 | 36 hrs. | 75 | 3,587 |
| 12 hrs. | 180 | 3,663 | 46 hrs. | 35 | |
| 14 hrs. | 170 | 3,660 | | | |

Effective Injection Time 373 min.
Injection Rates 59 min. at 196 GPM
314 min. at 392 GPM

Volume of D[illegible] City Water Injected 3,240 bbls.

The Amerada bomb was set at 8,000' for safety precautions.

ROCKY MOUNTAI
PRESSURE INJECTION I
SUMMARY OF PRESSURE

| Date | Operation | $\Delta V$ barrels | $\Sigma \Delta V$ barrels | Fluid | $\rho$ fluid | $Z_b$ ft | Z |
|---|---|---|---|---|---|---|---|
| 9-3- 61 | Coring | 450 | 450 | | | | |
| 9-5- 61 | DST #13 | 75 | 375 | Muddy formation water | 1.06 | 9,645 | 2, |
| 9-6- 61 | DST #14 | 75 | 300 | Formation water | 1.05 | 11,007 | |
| 9-8- 61 | Injection Test | 190 | 490 | Fresh water | 1.00 | | |
| 9-10-61 | Drilling | 477 | 967 | | | | |
| 9-12-61 | Drilling | 270 | 1,187 | | | | |
| 9-14-61 | Drilling | 72 | 1,259 | | | | |
| 9-18-61 | Injection Test | 401 | 1,660 | Fresh water | 1.00 | 11,975 | |
| 9-19-61 | Injection Test | 692 | 2,352 | Fresh water | 1.00 | 11,975 | |
| 9-20-61 | Injection Test | 1,574 | 3,926 | Fresh water | 1.00 | 11,975 | |
| 9-21-61 | $P_s$ Test | | | | | | |
| 9-22-61 | Air Lift | -1,100 | 2,826 | | | | |
| 9-23-61 | Air Lift | -795 | 2,031 | | | | |
| 9-25-61 | Air Lift | -509 | 1,522 | | | | |
| 10-6-61 | Fluid Level | | | | | | |
| 10-11-61 | Pumping | -79 | 1,443 | | | | |
| 10-12-61 | Pumping | -267 | 1,176 | | | | |
| 10-13-61 | Pumping | -188 | 988 | | | | |
| 10-19-61 | Pumping | -342 | 646 | | | | |
| 10-20-61 | Pumping | -285 | 361 | | | | |
| 10-21-61 | Pumping | -220 | 121 | | | | |
| 10-23-61 | Pumping | -424 | -303 | | | | |
| 11-1 -61 | Pumping | -185 | -488 | | | | |
| 11-3 -61 | $P_s$ Test | | | | | | |
| 11-8 -61 | Pumping | -256 | -744 | | | | |
| 11-16-61 | Pumping | -143 | -887 | | | | |
| 11-22-61 | Pumping | -353 | -1,240 | | | | |
| 11-27-61 | End Pumping | -202 | -1,402 | | | | |
| 12-1 -61 | $P_s$ Test | 0 | -1,402 | Formation water | | 12,000 | |
| 12-21-61 | $P_s$ Test | 0 | -1,402 | Formation water | | 12,000 | |
| 1-3 -62 | Inj. Test #1 | 4,534 | 3,132 | Fresh water | 1.00 | 5 | 12, |
| 1-5 -62 | Inj. Test #2 | 3,380 | 6,180 | Fresh water | 1.00 | 3,000 | 9, |
| 1-17-62 | $P_s$ Test | 0 | 6,180 | Fresh water | 1.00 | 8,500 | 3, |
| 1-22-62 | Inj. Test #3 | 3,450 | 9,630 | Fresh water | 1.00 | 7,500 | 4, |
| 1-25-62 | Inj. Test #4 | 3,240 | 12,870 | Fresh water | 1.00 | 8,000 | 4, |

A

Table 13

Y MOUNTAIN ARSENAL
NJECTION DISPOSAL WELL
PRESSURE TEST RESULTS

| $Z_b$ ft | $Z_d - Z_b$ ft | $\Delta P$ cor psi | $P_s$ psi | $P^*$ psi | $P_{im}$ psi | Kh md-ft | F. E. % | $r_{ft}$ |
|---|---|---|---|---|---|---|---|---|
| 9,645 | 2,355 | 1,082 | 4,968 | 4,910 | 4,814 | 431 | 44 | 302 |
| 11,007 | 997 | 459 | | 4,694 | 4,522 | 173 | 87 | 177 |
| 1,975 | 25 | 11 | | | | | | |
| 1,975 | 25 | 11 | | | | | | |
| 1,975 | 25 | 11 | 4,943 | | | | | |
| | | | 5,024 | | | | | |
| | | | 4,359 | | | | | |
| | | | 3,040 | | | | | |
| 2,000 | 0 | 0 | 2,125? | | | | | |
| 2,000 | 0 | 0 | 2,613 | | | | | |
| [illegible] | 12,000 | 5,196 | 2,714 | 5,174 | 5,196 | 3,390 | 52 | 768 |
| 3,000 | 9,000 | 3,897 | 4,756 | 5,244 | 5,180 | 11,260 | 53 | 1,522 |
| 8,500 | 3,500 | 1,516 | 4,824 | | | | | |
| 7,500 | 4,500 | 1,949 | 5,114 | 5,282 | 5,109 | 6,110 | 78 | 3,980 |
| 8,000 | 4,000 | 1,732 | 5,143 | 5,389 | 5,291 | 8,700 | 68 | 6,200 |

B

Table 14

ROCKY MOUNTAIN ARSENAL
PRESSURE INJECTION DISPOSAL WELL
CORE DESCRIPTION

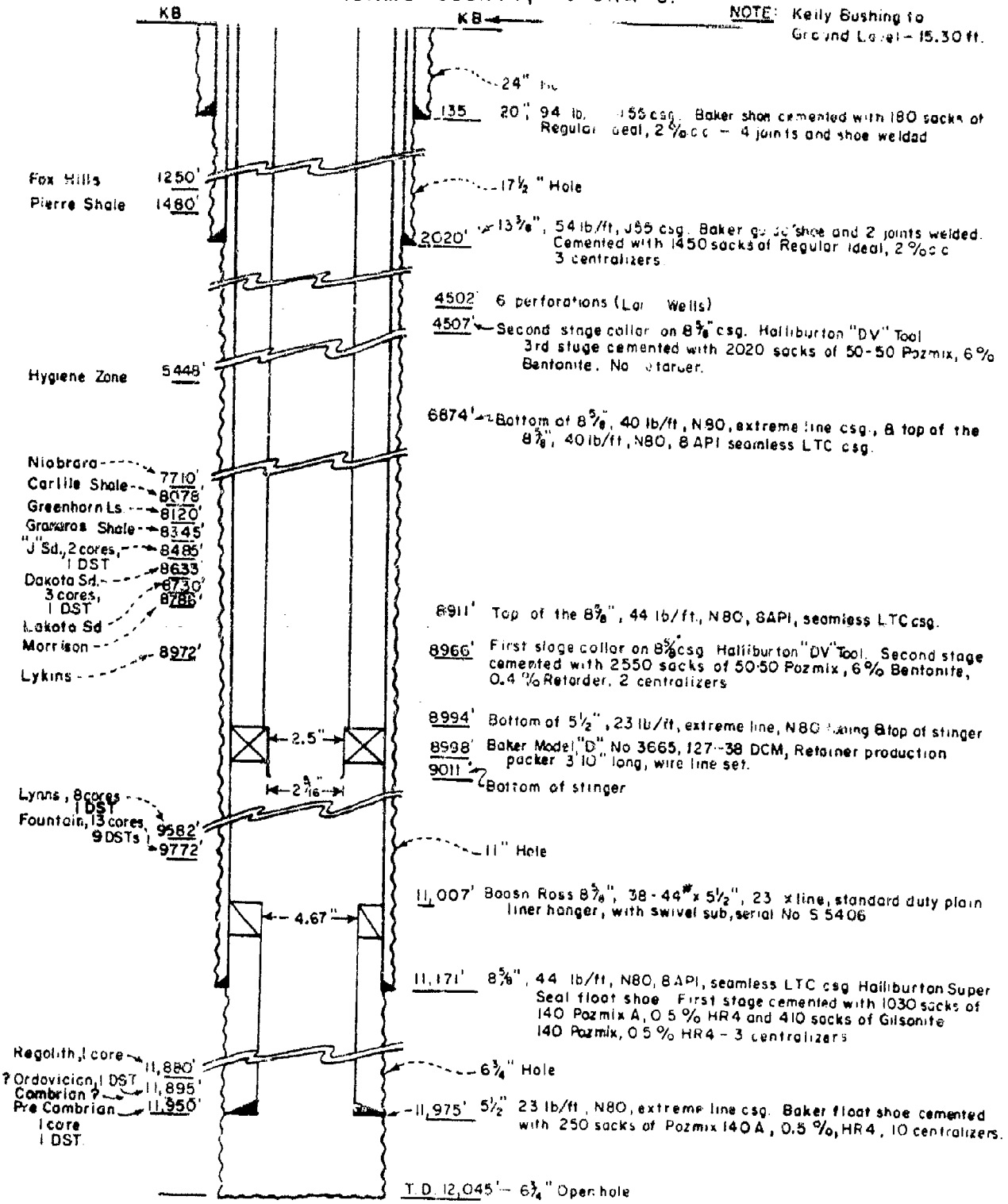
Core No. 28

| | |
|---|---|
| Interval: | Pre-Cambrian |
| Depth: | 11,976-11,985' |
| Cut 9': | Recovered 6.7' |
| 6.0': | Biotite, hornblende, granite gneiss, fractured |
| 0.7': | Biotite, hornblende, granite gneiss, and pegmatite |

# CASING AND HOLE DETAILS

FIGURE 1

PRESSURE INJECTION DISPOSAL WELL
ROCKY MOUNTAIN ARSENAL
SECTION 26, T2S-R67W
ADAMS COUNTY, COLORADO.

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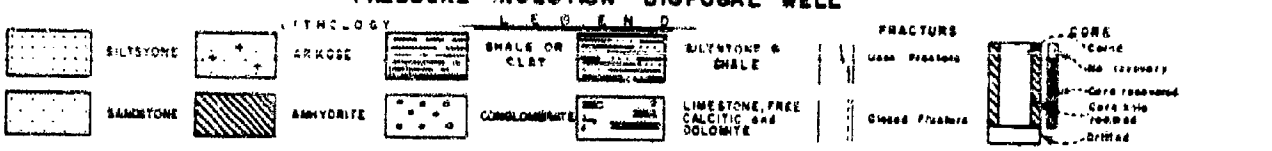
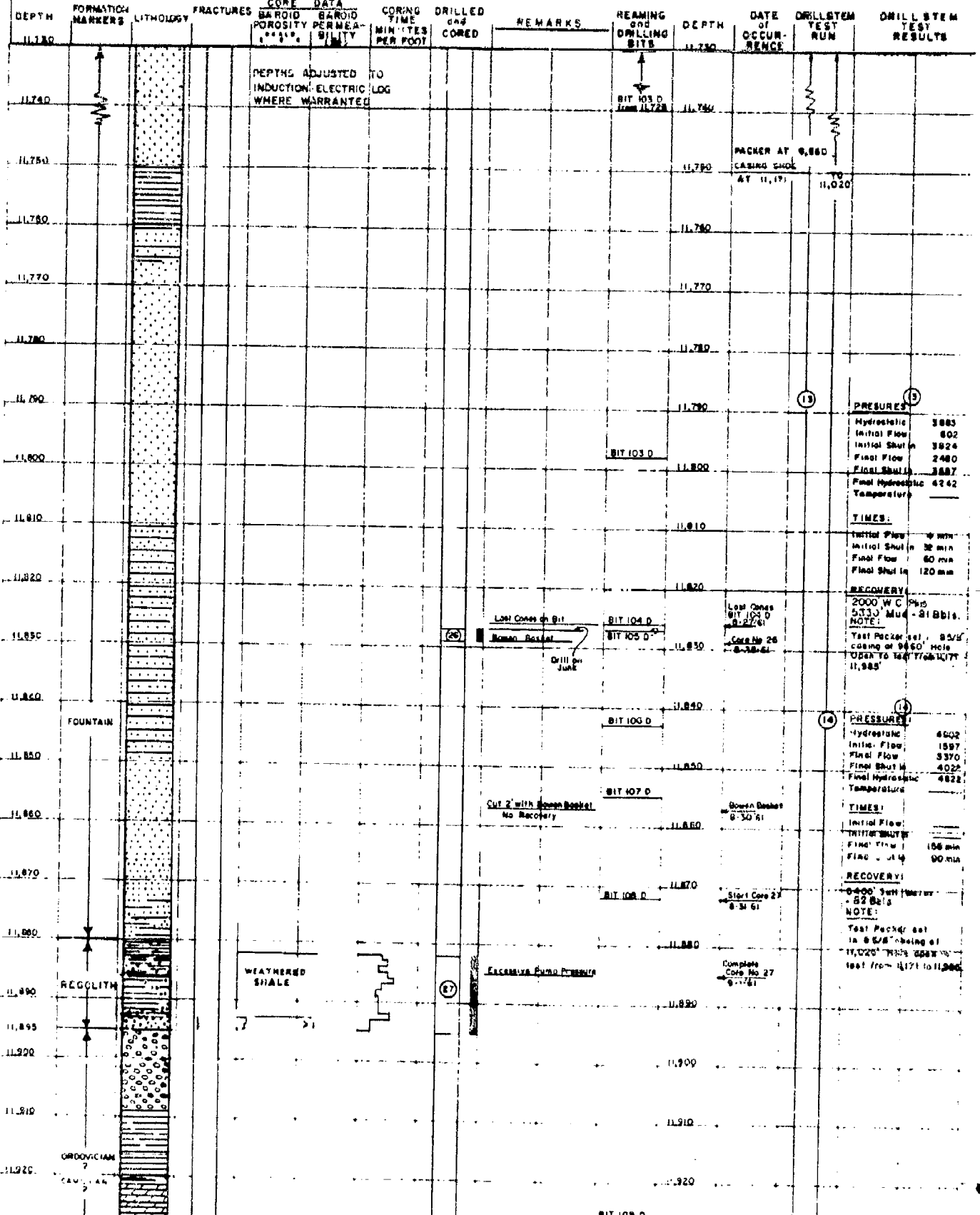
# GRAPHICAL REPRESENTATION OF FORMATION EVALUATION DATA

FIG 2

NO 12
INTERVAL 11,730 – 12,080'

## ROCKY MOUNTAIN ARSENAL
## PRESSURE INJECTION DISPOSAL WELL



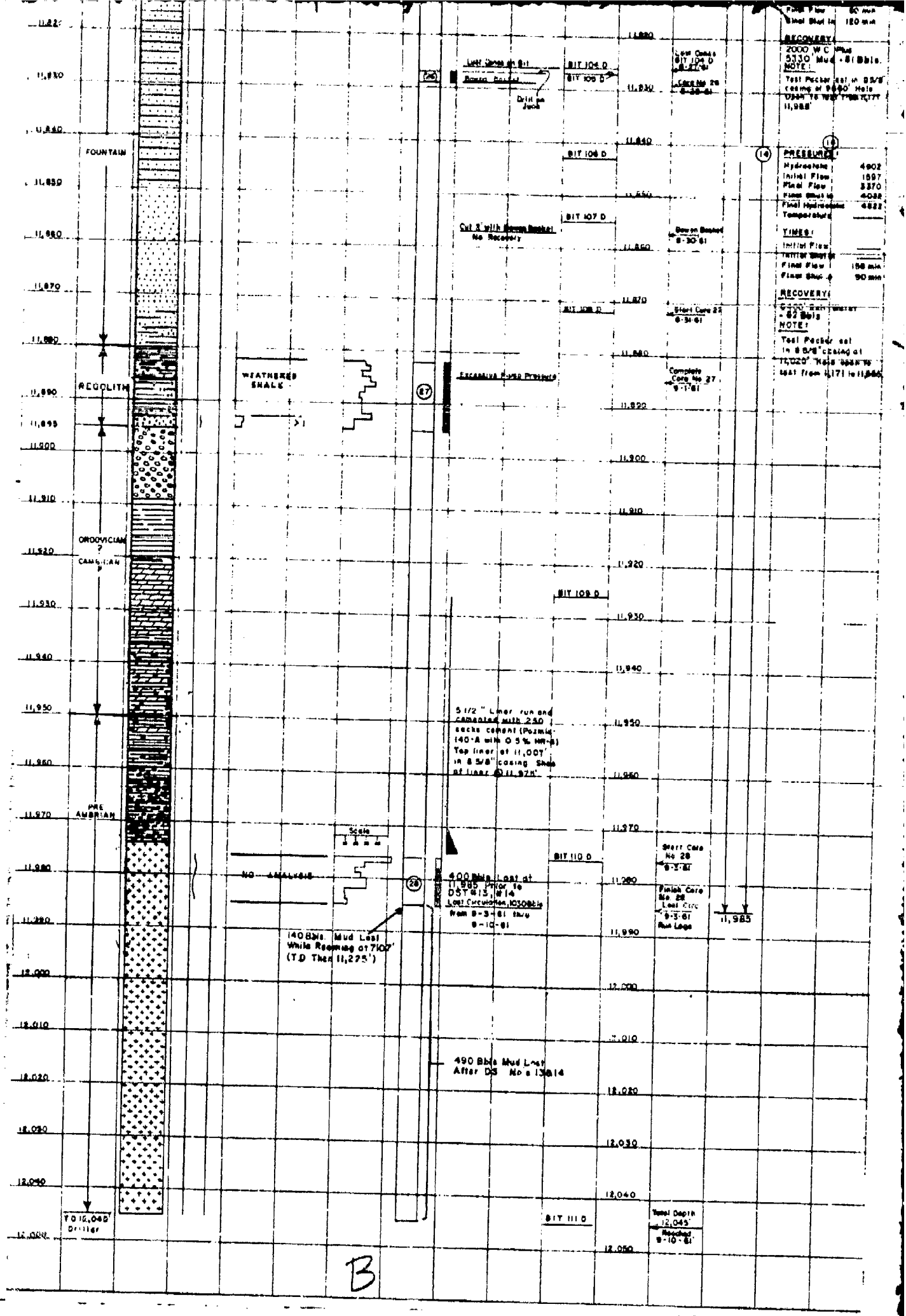
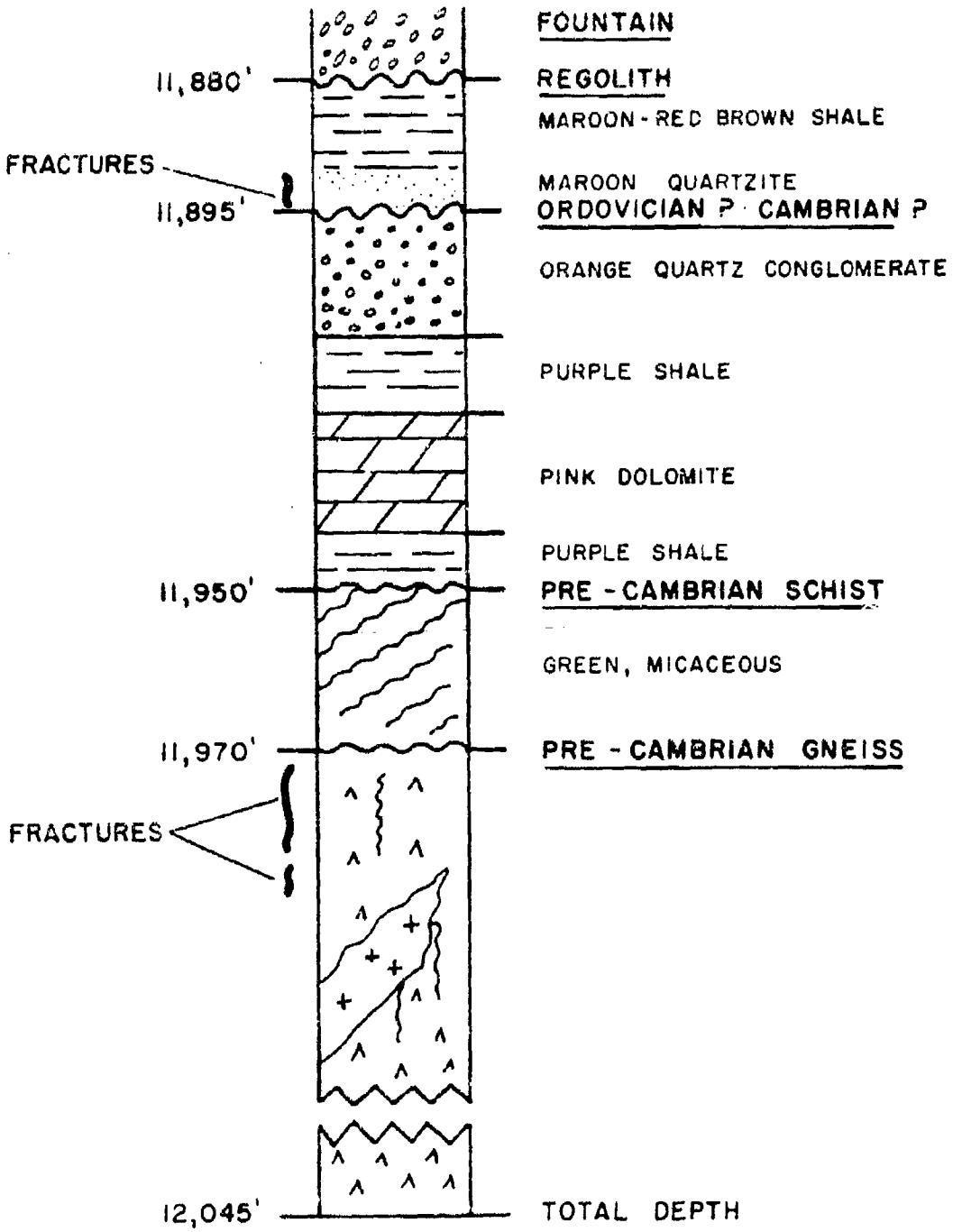

FOUNTAIN
REGOLITH
ORDOVICIAN ?
CAMBRIAN ?
PRE AMBRIAN
T.D 12,045' Driller
WEATHERED SHALE
Excessive Fluid Pressure
No Analysis
Scale
140 Bbls. Mud Lost While Reaming at 7100' (T.D Then 11,275')
400 Bbls. Lost at 11,985 Prior to DST #13, #14
Lost Circulation, 10308 Bbls from 8-3-61 thru 8-10-61
5 1/2" Liner run and cemented with 250 sacks cement (Pozmix 140-A with 0.5% HR-8) Top liner at 11,001' in 8 5/8" casing Shoe of liner @ 11,974'
490 Bbls Mud Lost After DS No s 13&14
Lost Circ at 81
Broken Bucket
Drill on Jacks
Cut 3' with Brown Barrel No Recovery
Excessive Fluid Pressure
Short Core No 28 8-31-61
Complete Core No 27 9-1-61
Short Core No 28 9-3-61
Finish Core No 28 Lost Circ 9-3-61 Run Logs
11,985
Total Depth 12,045' Reached 9-10-61
BIT 104 D
BIT 105 D
BIT 106 D
BIT 107 D
BIT 108 D
BIT 109 D
BIT 110 D
BIT 111 D
Lost Circ BIT 104 D 8-27-61
Core No 26 8-28-61
Brown Barrel 8-30-61
Short Core 28 8-31-61
Complete Core No 27 9-1-61
Short Core No 28 9-3-61
Finish Core No 28 Lost Circ 9-3-61 Run Logs
Total Depth 12,045' Reached 9-10-61
RECOVERY: 2000 W C Plus 5330' Mud - 81 Bbls.
NOTE: Test Packer set in 8 5/8" casing at 9680' Hole Open To 11,988'
PRESSURES:
Hydrostatic 4902
Initial Flow 1897
Final Flow 3370
Final Shut-in 4032
Final Hydrostatic 4822
Temperature —
TIMES:
Initial Flow —
Initial Shut-in —
Final Flow 150 min
Final Shut-in 90 min
RECOVERY: - 62 Bbls
NOTE: Test Packer set in 8 5/8" casing at 11,020' Hole open to test from 11,171 to 11,845
B

FIGURE 3

# ROCKY MOUNTAIN ARSENAL
# PRESSURE INJECTION DISPOSAL WELL

## PRE - FOUNTAIN GEOLOGIC COLUMN

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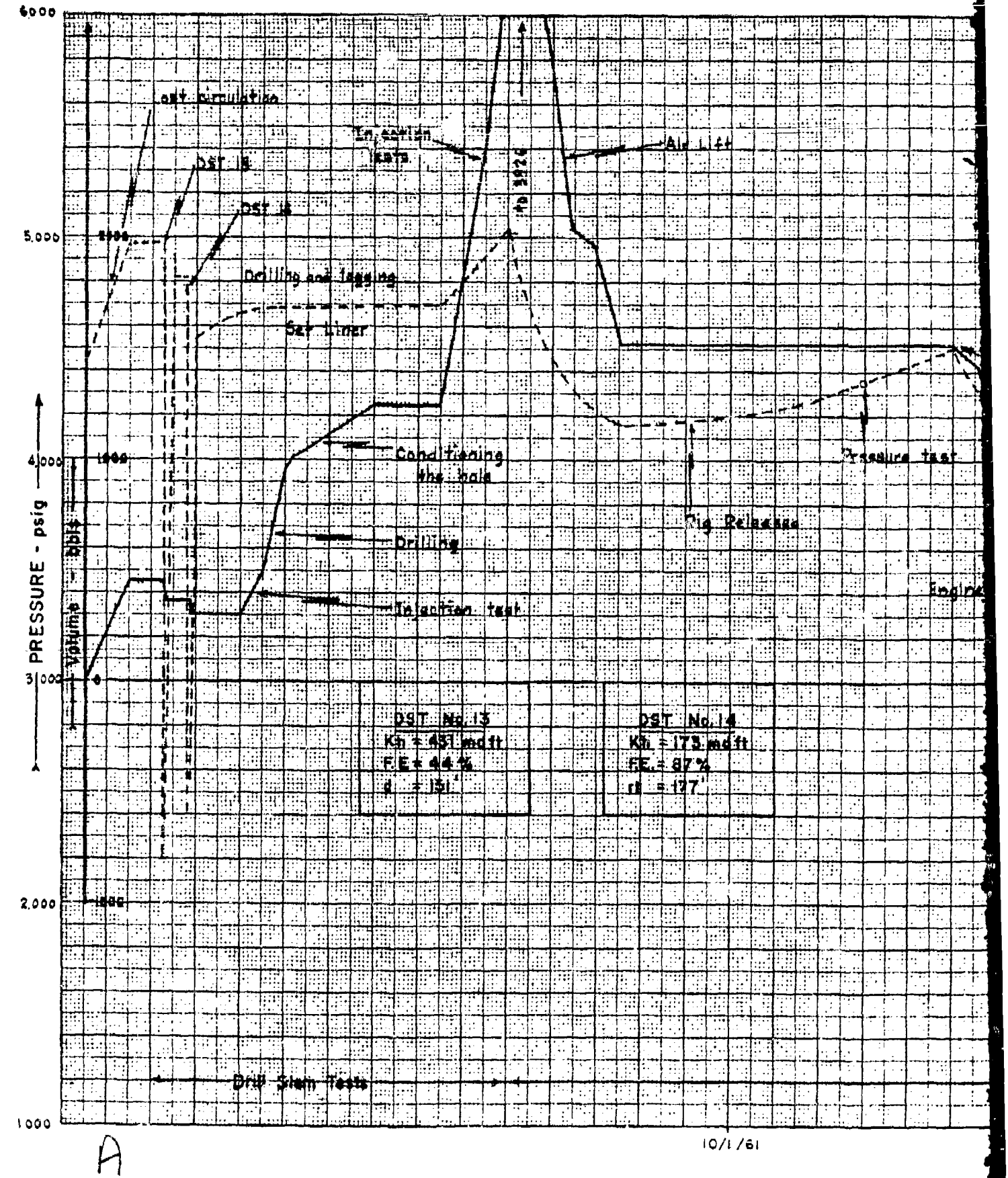
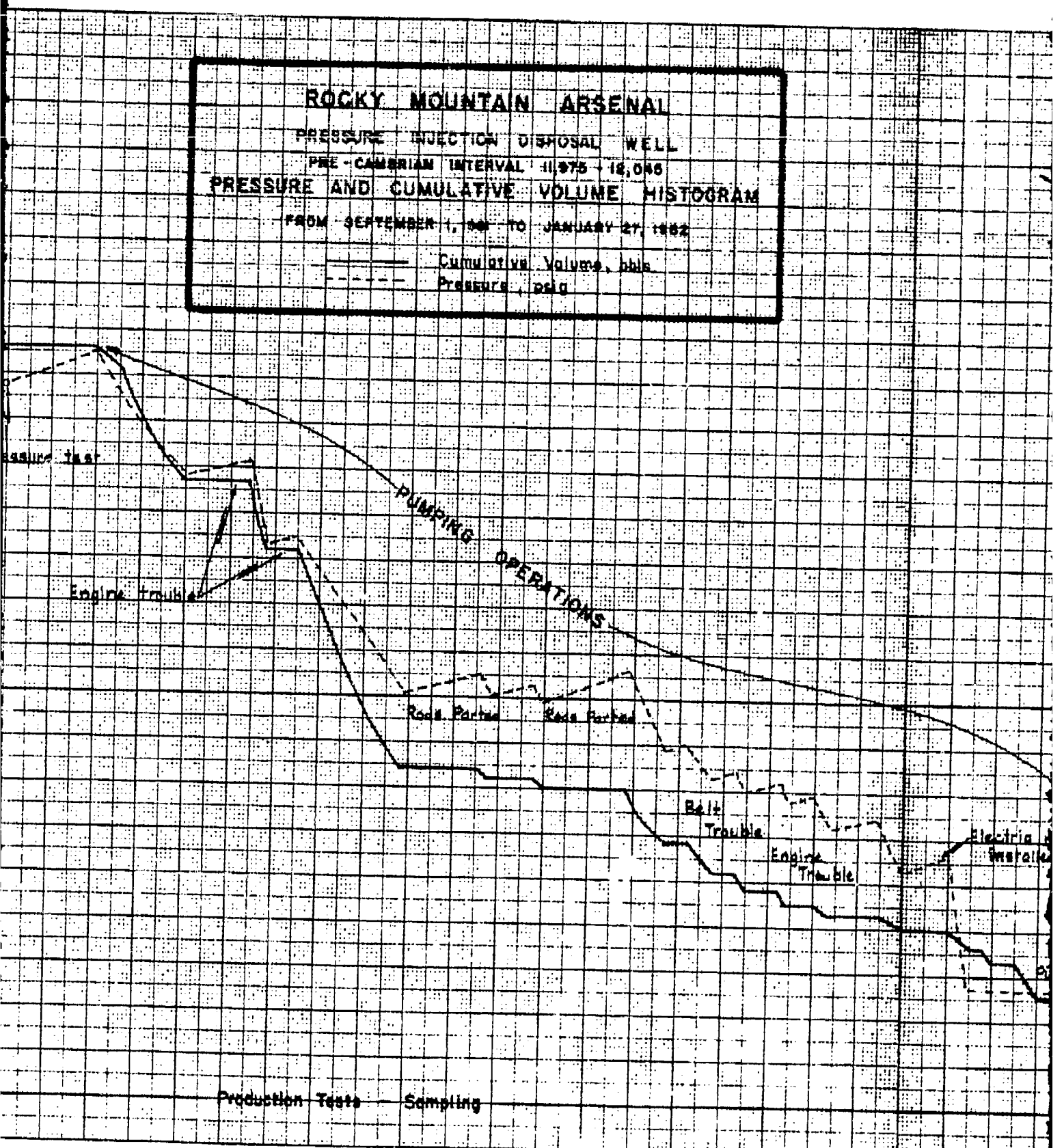
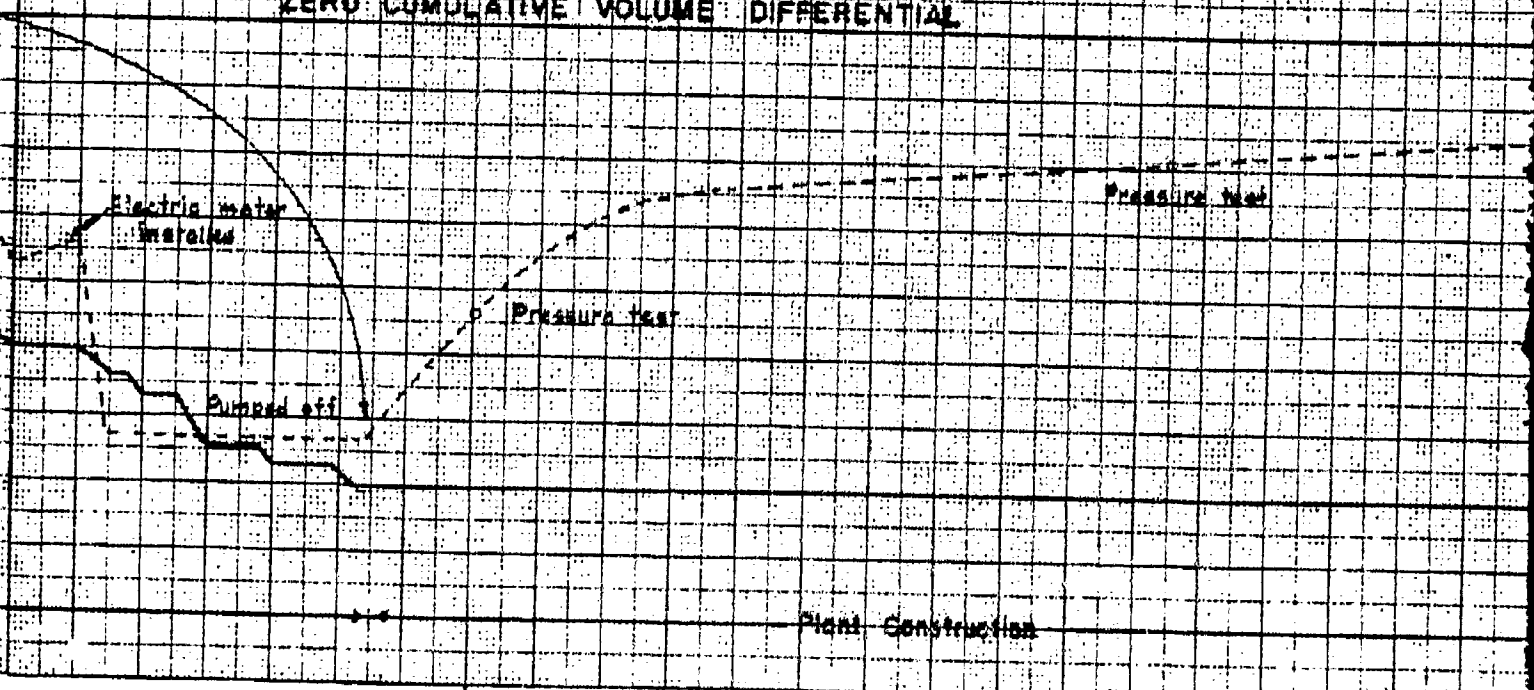

6,000
5,000
4,000
3,000
2,000
1,000
PRESSURE - psig
Volume - bbls
Drill Stem Tests
DST No. 13
Kh = 451 md ft
F.E. = 44 %
rd = 151'
DST No. 14
Kh = 173 md ft
F.E. = 87 %
rd = 177'
Conditioning the hole
Drilling
Injection test
Pressure test
Rig Released
Engine
Drilling and logging
Set Liner
Air Lift
10/1/61
A


ROCKY MOUNTAIN ARSENAL
PRESSURE INJECTION DISPOSAL WELL
PRE-CAMBRIAN INTERVAL 11,975 - 12,045
PRESSURE AND CUMULATIVE VOLUME HISTOGRAM
FROM SEPTEMBER 1, 1961 TO JANUARY 27, 1962
Cumulative Volume, bbls
Pressure, psig
PUMPING OPERATIONS
Engine Trouble
Rods Parted
Rods Parted
Belt Trouble
Engine Trouble
Production Tests
Sampling
11/1/61
TIME
E. A. POLUMBUS, JR. AND ASSOCIATES, INC.

B

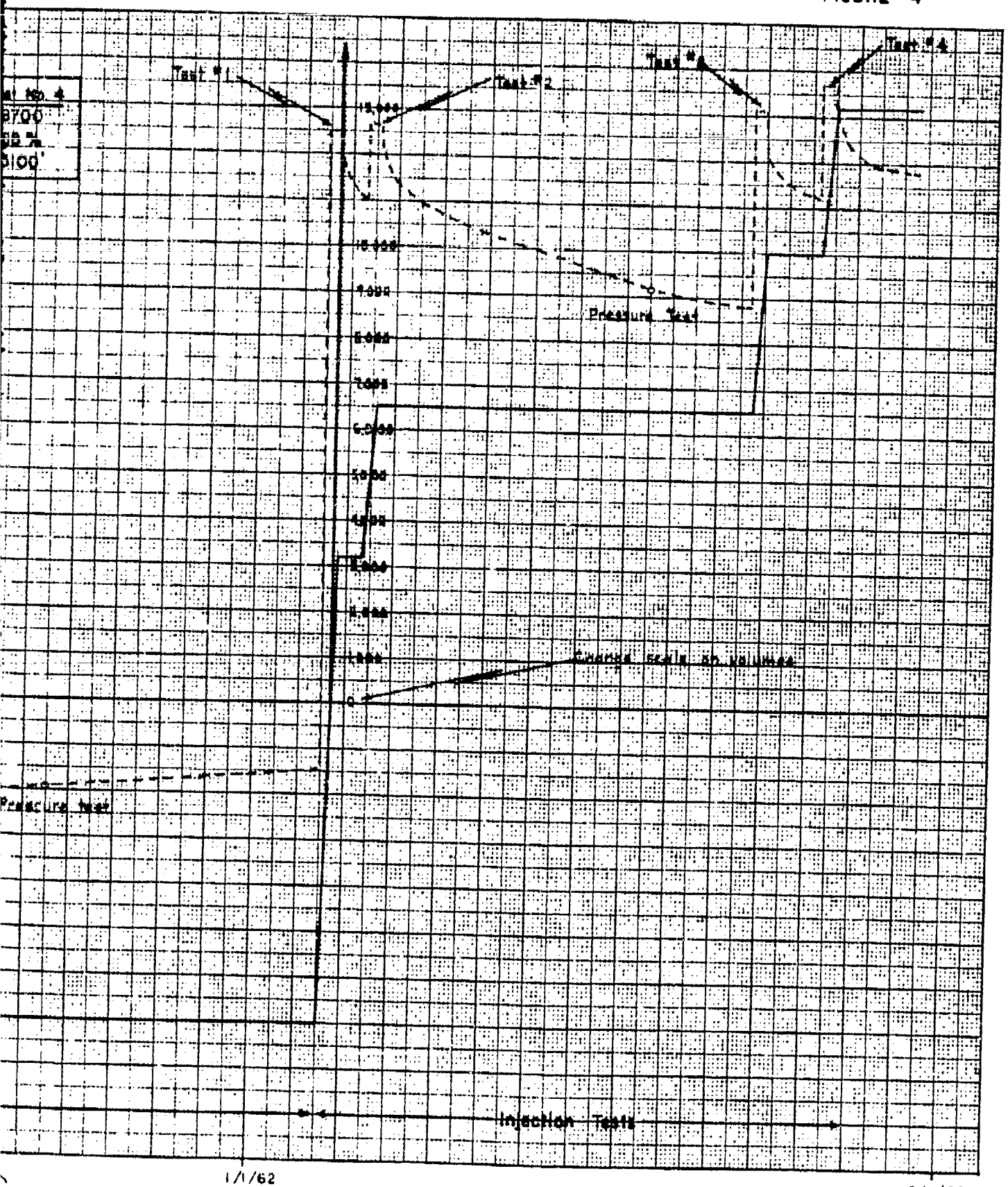
| Inj. Test No.1 | Inj. Test No.2 | Inj. Test No. 3 | Inj. Test No. 4 |
|---|---|---|---|
| Kh = 3390 | Kh = 11,260 | Kh = 6110 | Kh = 6704 |
| F.E. = 52 % | F.E. = 53 % | F.E. = 78 % | F.E. = 65 % |
| d = 384 | d = 781' | d = 1890' | d = 3100' |

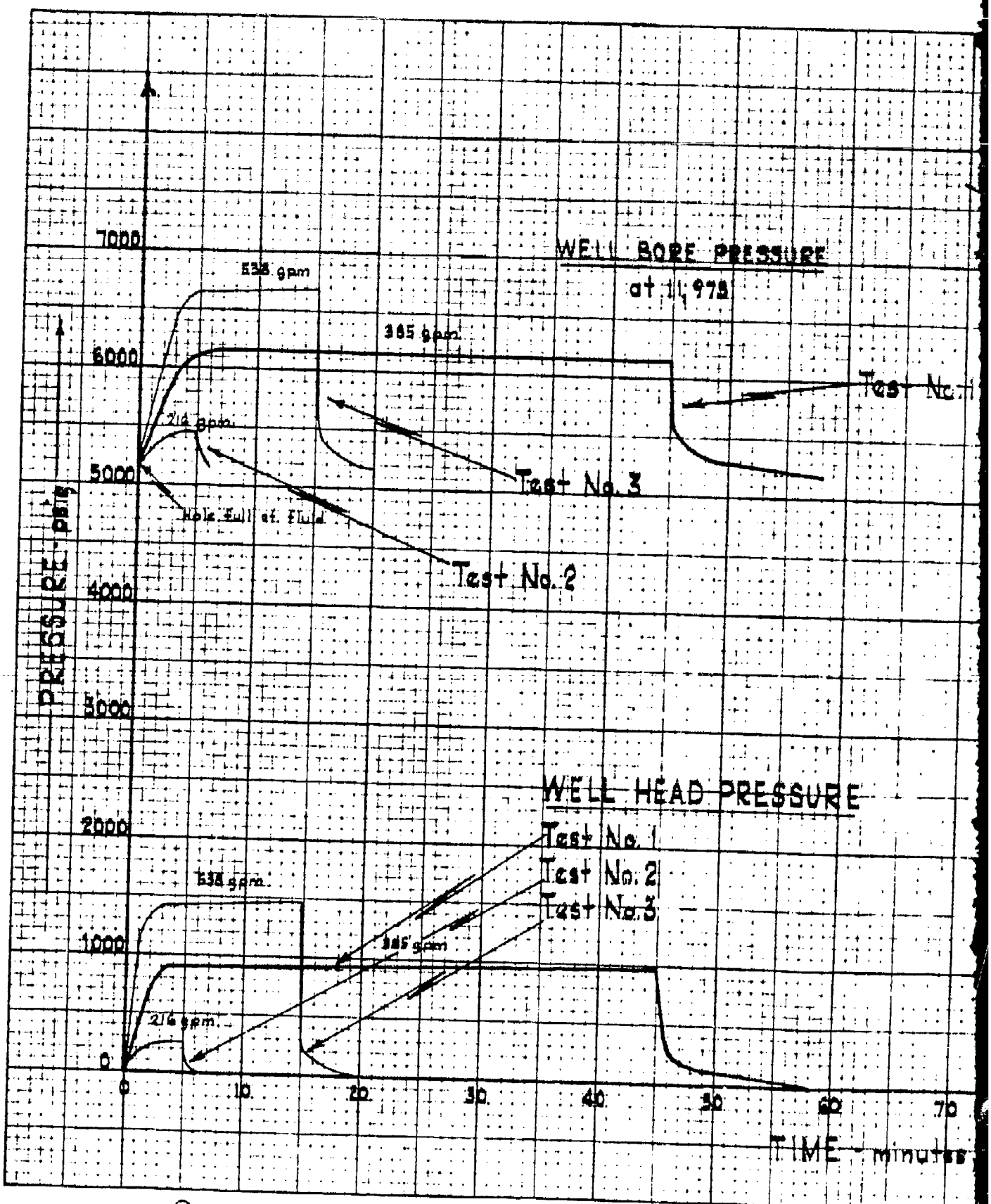



ME

AND ASSOCIATES, INC

FIGURE 4

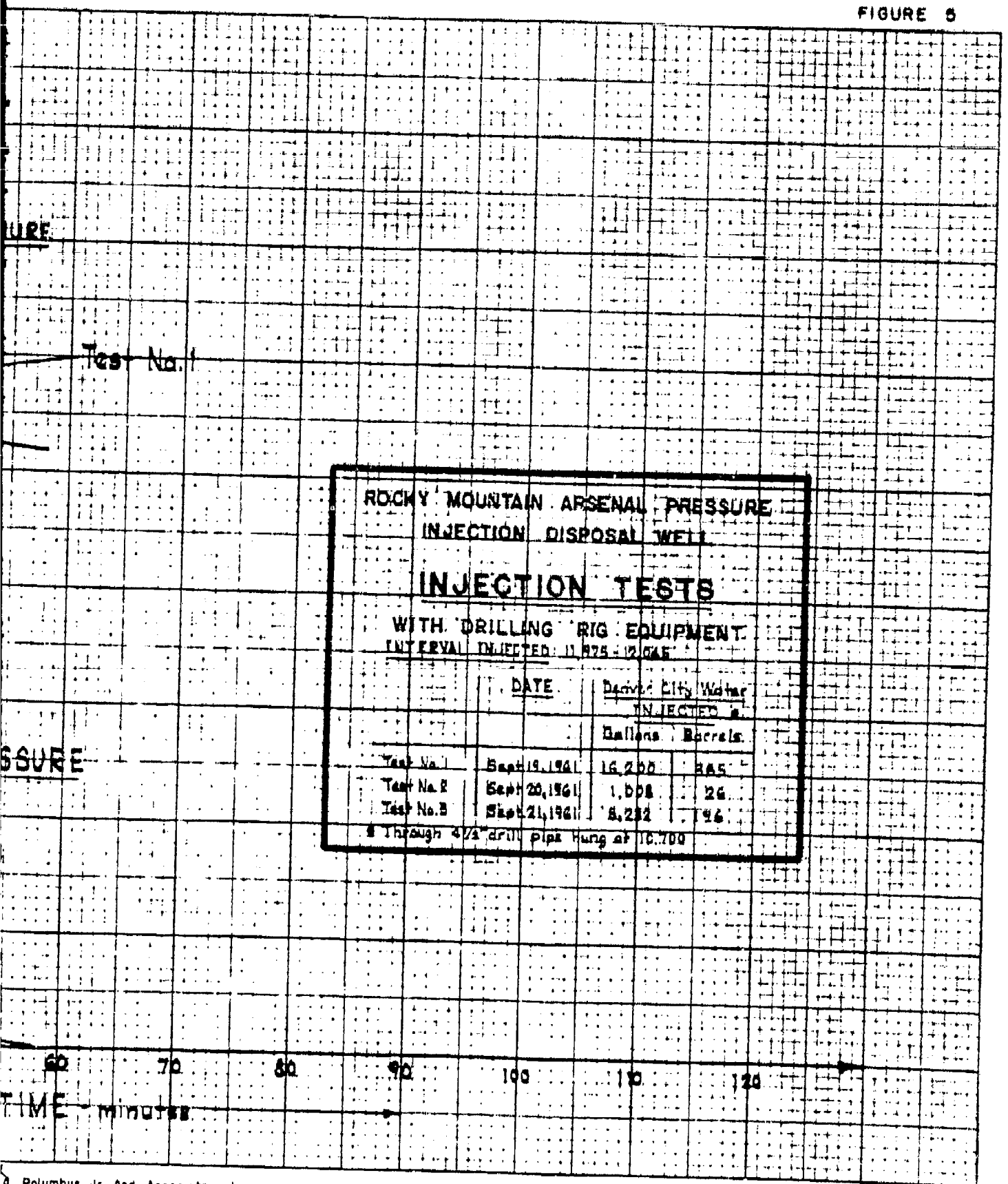

Test #1
Test #2
Test #3
Test #4
Pressure Test
Pressure Test
Injection Tests
1/1/62
2/ /62




A

E. A Polumbus, Jr And Associa

FIGURE 5




ROCKY MOUNTAIN ARSENAL PRESSURE INJECTION DISPOSAL WELL

## INJECTION TESTS

WITH DRILLING RIG EQUIPMENT

INTERVAL INJECTED 11,975 - 12,045'

| | DATE | Denver City Water INJECTED @ | |
|---|---|---|---|
| | | Gallons | Barrels |
| Test No. 1 | Sept 19, 1961 | 16,200 | 385 |
| Test No. 2 | Sept 20, 1961 | 1,008 | 24 |
| Test No. 3 | Sept 21, 1961 | 6,252 | 146 |

@ Through 4½" drill pipe hung at 10,700

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B

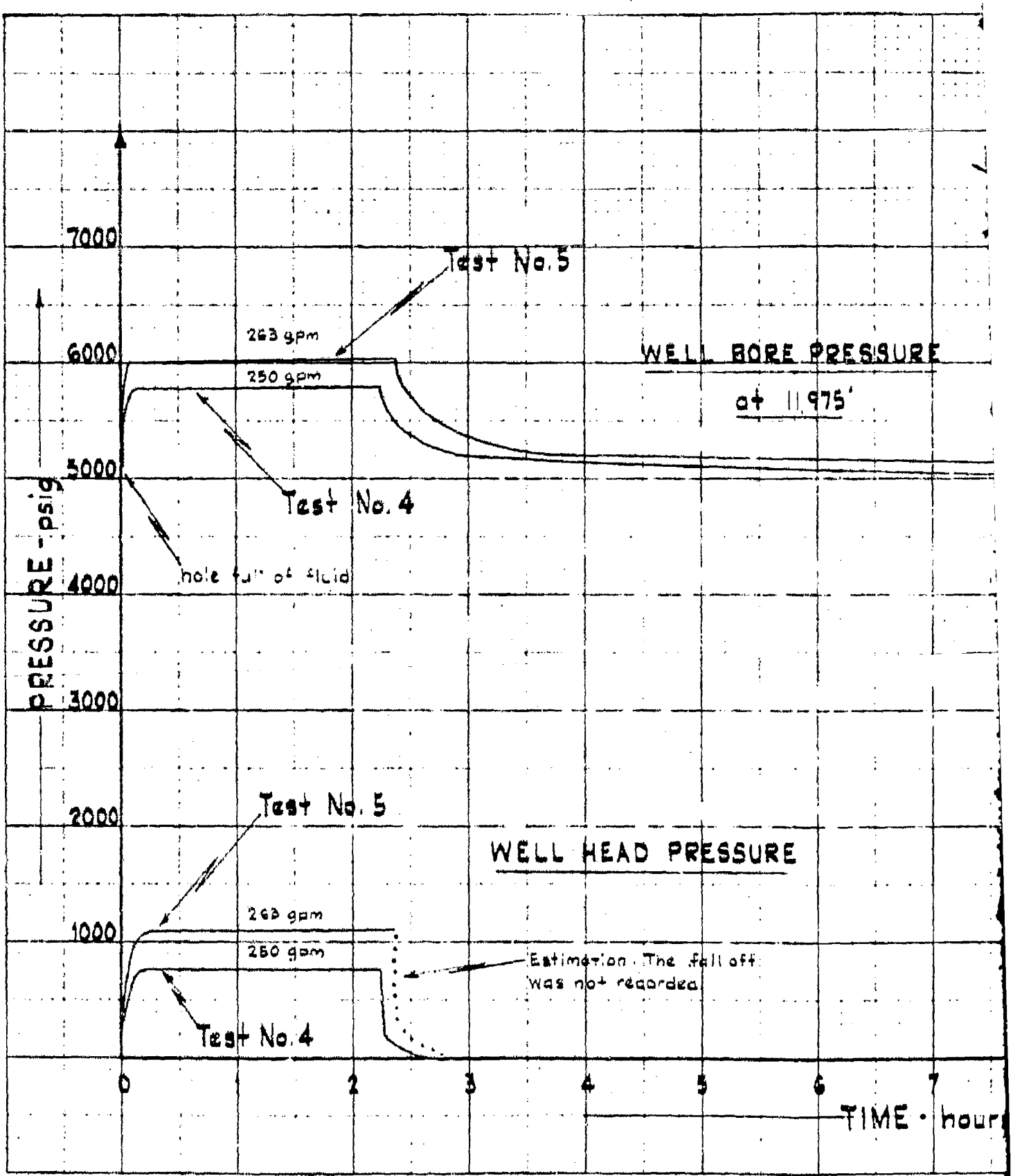


FIGURE 6

ORE PRESSURE

+ 11,975'

RE

ROCKY MOUNTAIN ARSENAL PRESSURE

INJECTION DISPOSAL WELL

## INJECTION TESTS

WITH DRILLING RIG EQUIPMENT

INTERVAL INJECTED : 11,975'- 12,045'

| | DATE | Denver City Water INJECTED | |
|---|---|---|---|
| | | Gallons | Barrels |
| Test No. 4 | Sept. 20, 1961 | 20,790 | 498 |
| Test No. 5 | Sept. 21, 1961 | 37,344 | 889 |

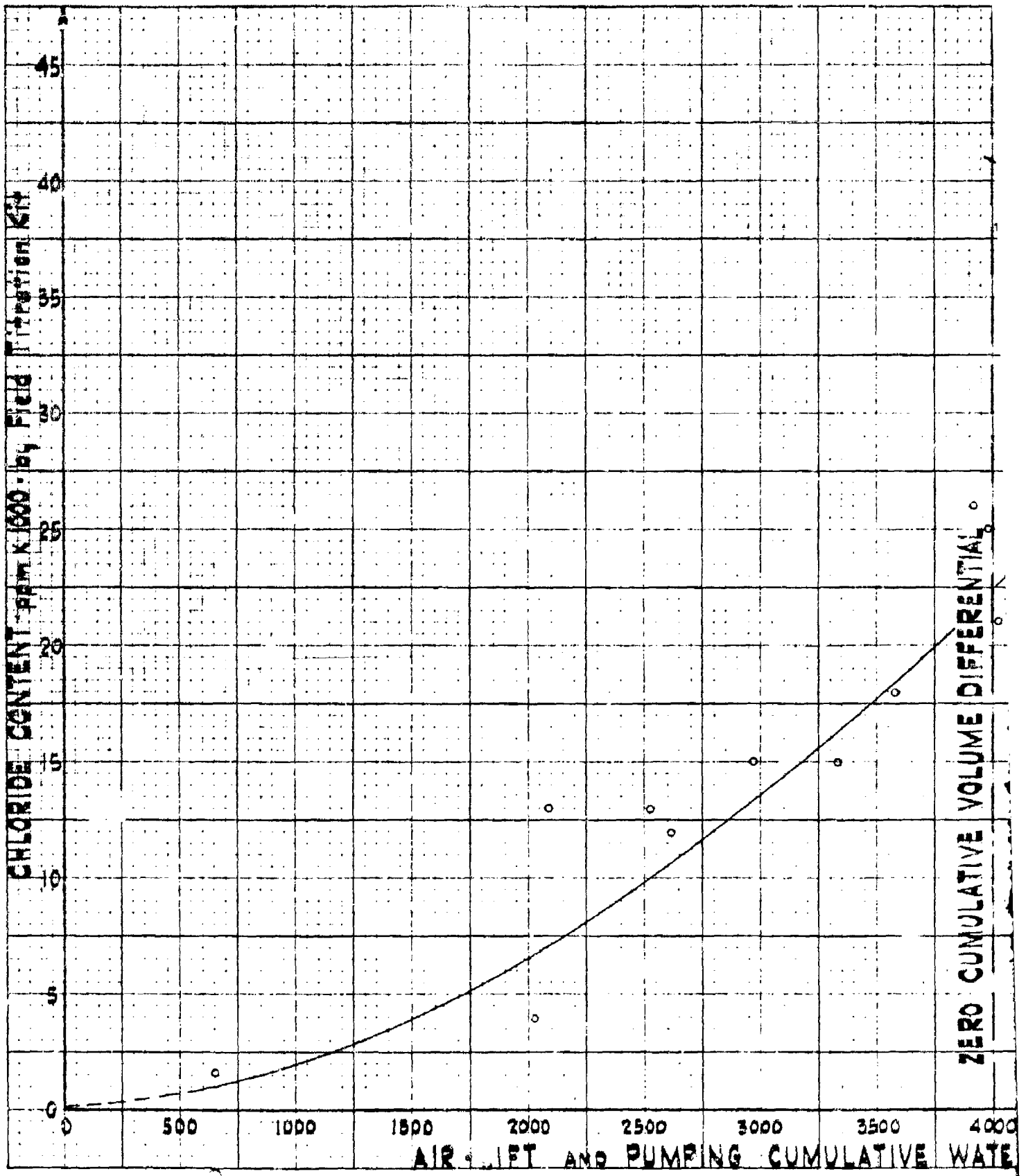
* Through 4½" drill pipe hung at 10,700'

6 7 8 9 10 11 12 13

TIME - hours

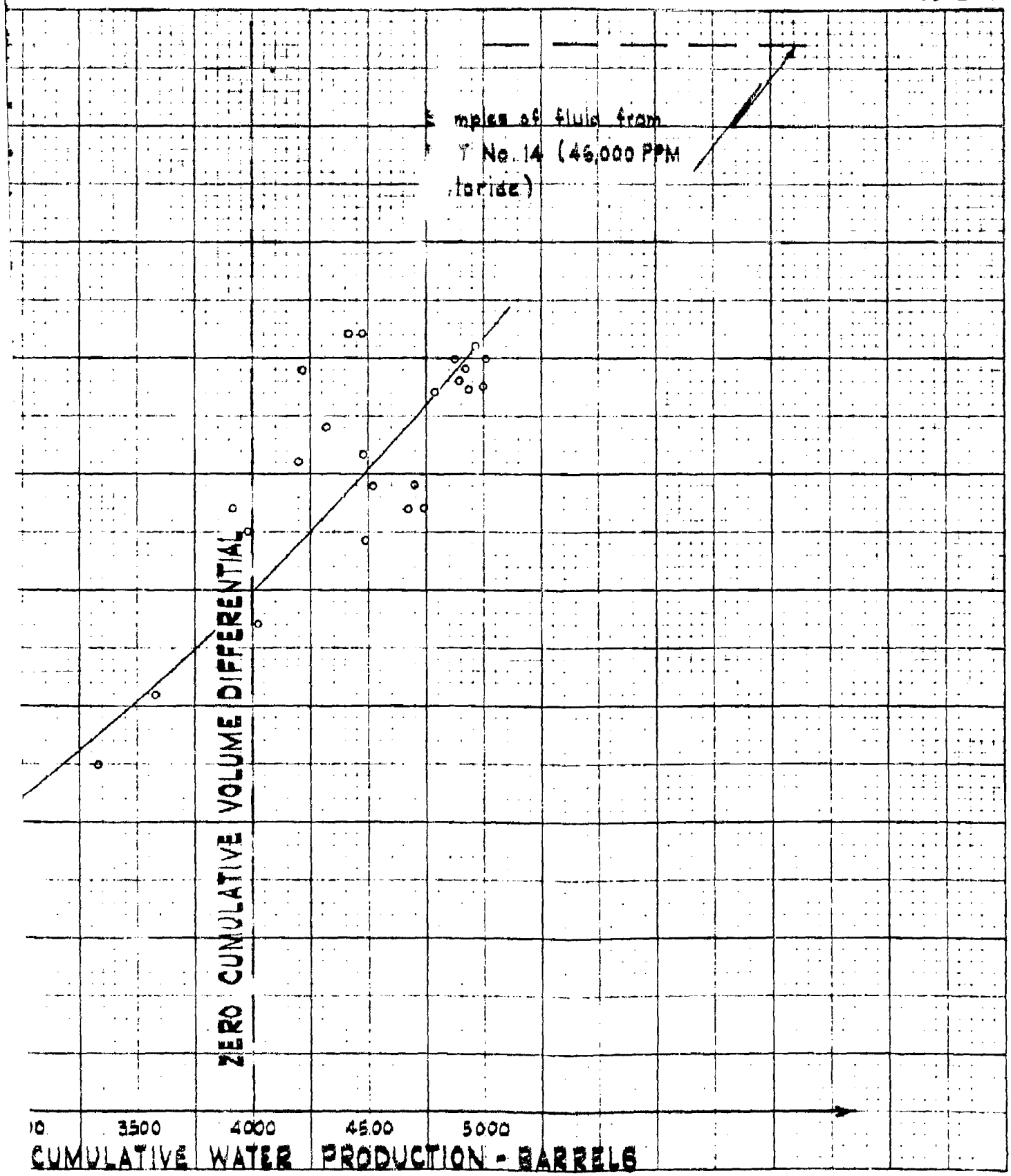
Palumbus, Jr And Associates, Inc

B


CHLORIDE CONTENT - ppm K 000 - by Field Titration KH
45
40
35
30
25
20
15
10
5
0
0
500
1000
1500
2000
2500
3000
3500
4000
ZERO CUMULATIVE VOLUME DIFFERENTIAL
AIR - LIFT AND PUMPING CUMULATIVE WATE
E A POLUMBUS, JR AND ASSOCIATES, INC

A1

FIGURE 7




COLUMBUS JR AND ASSOCIATES, INC

B

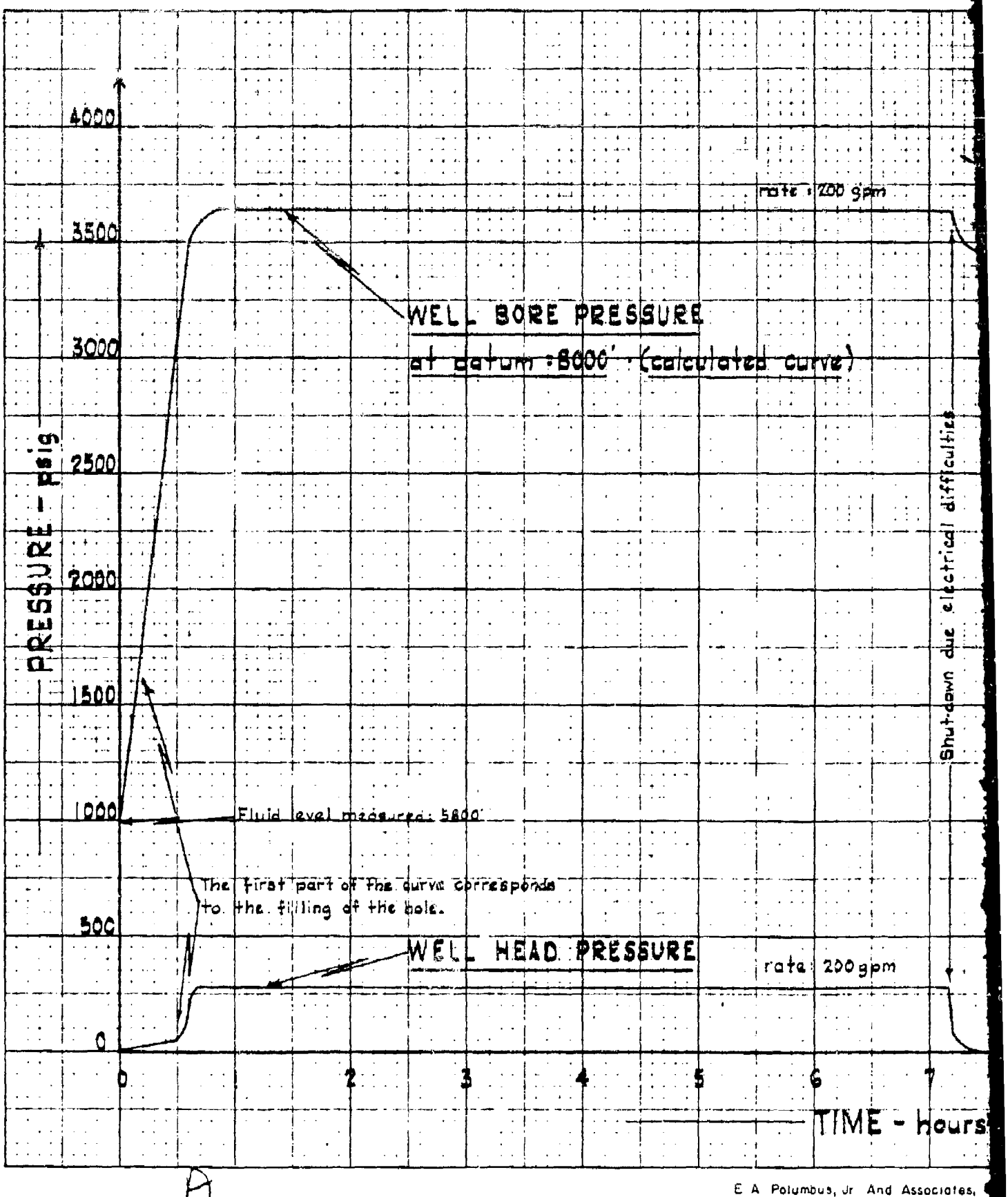



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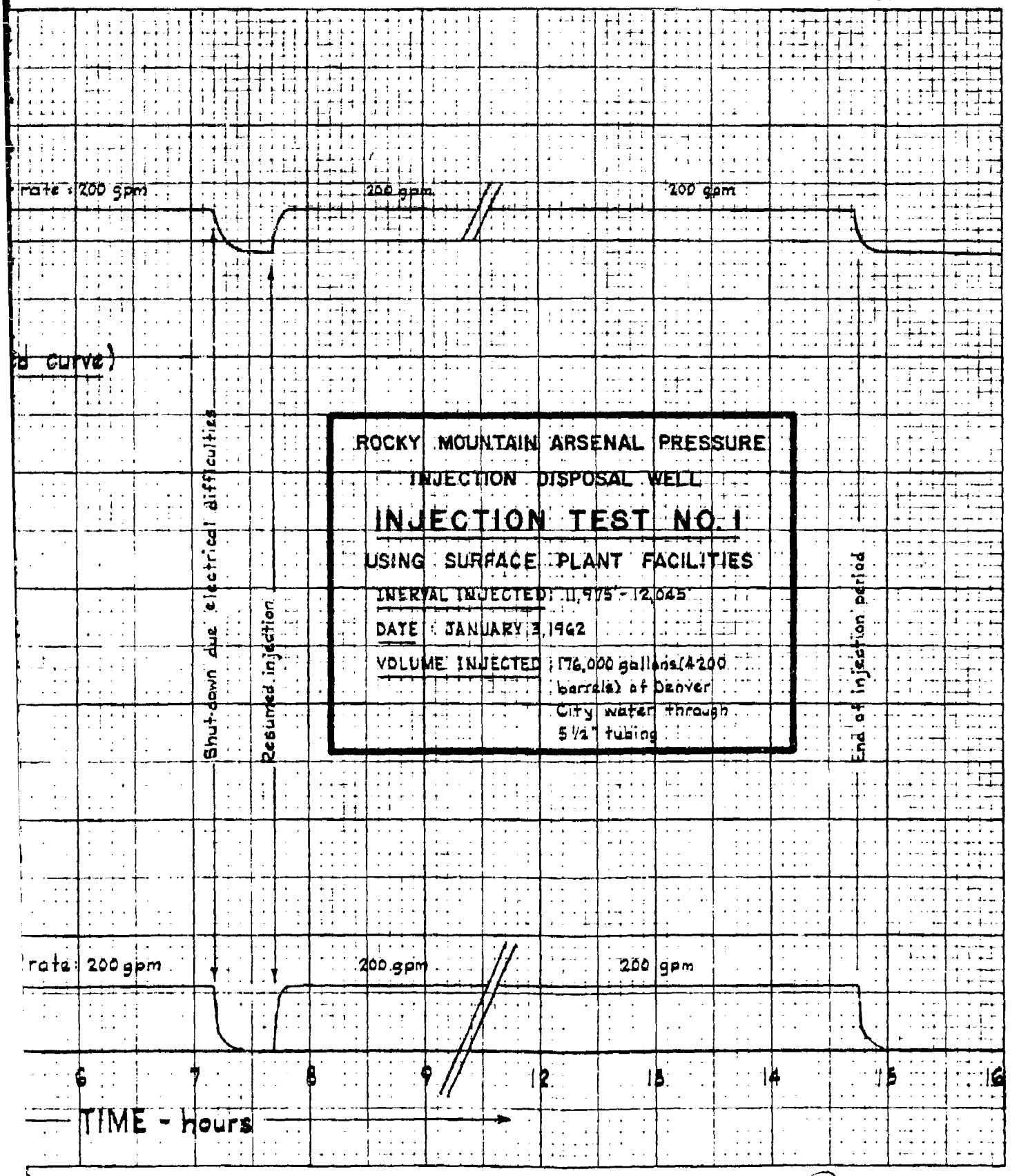
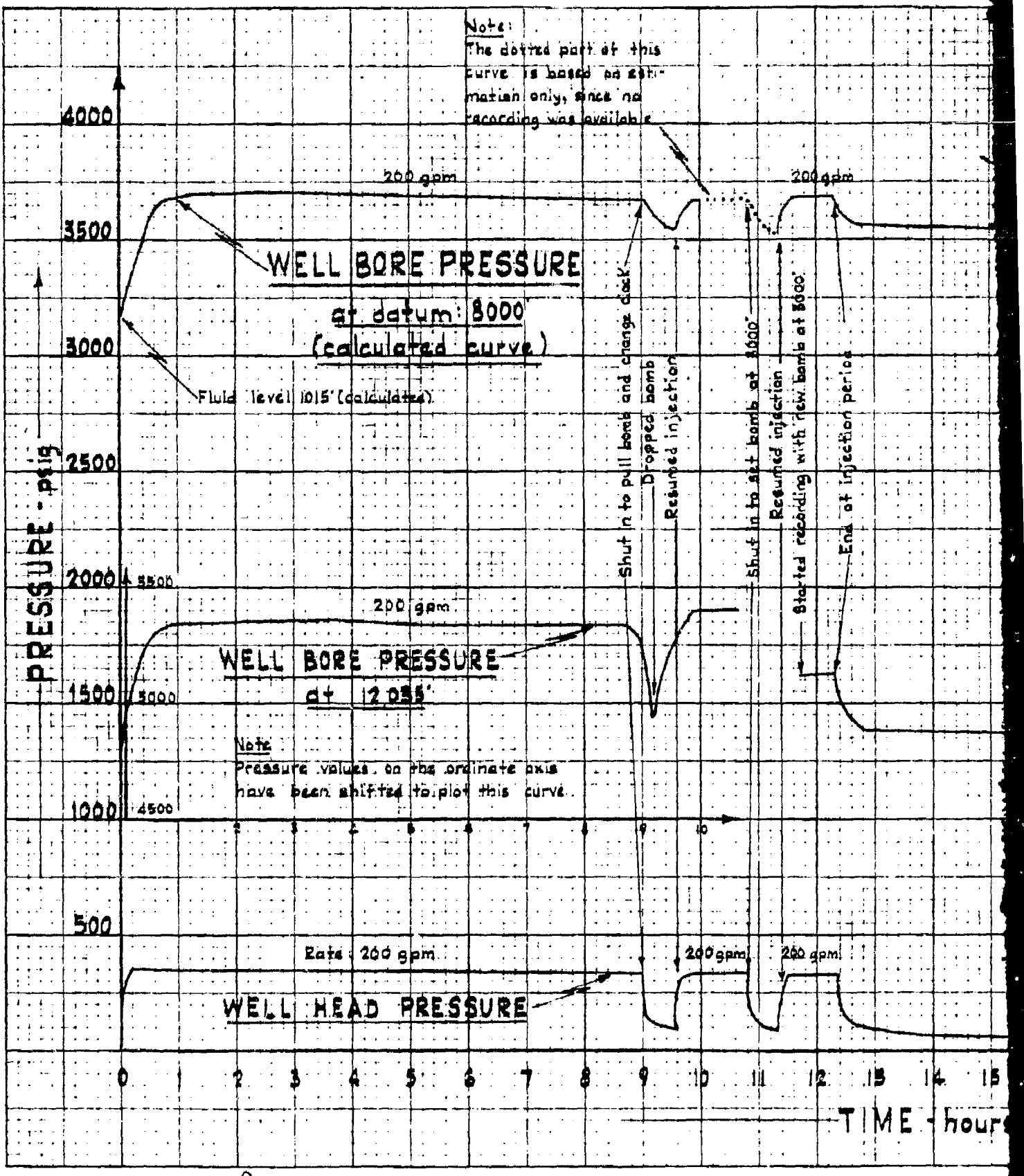
FIGURE 8



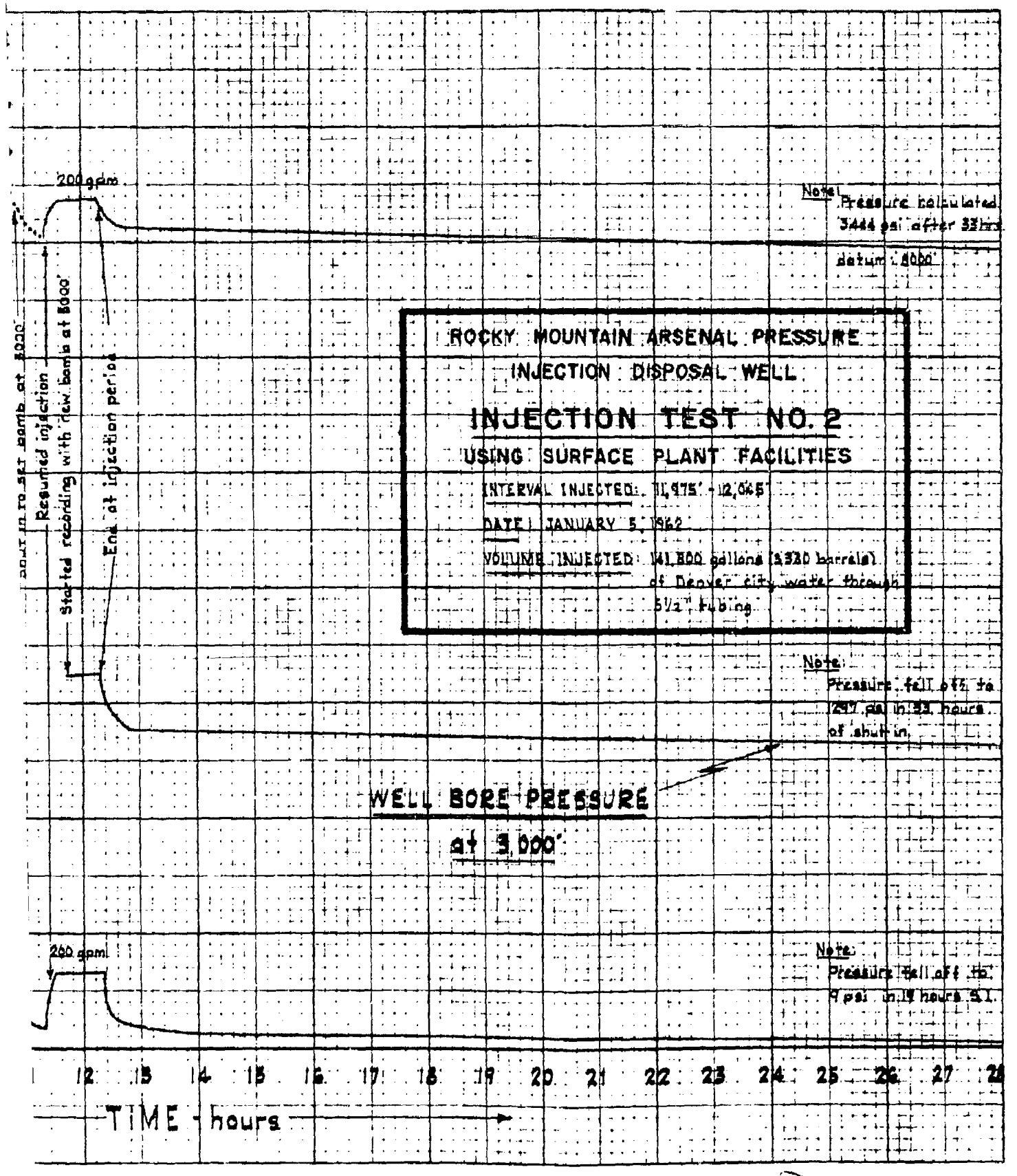

Columbus, Jr And Associates, Inc

B



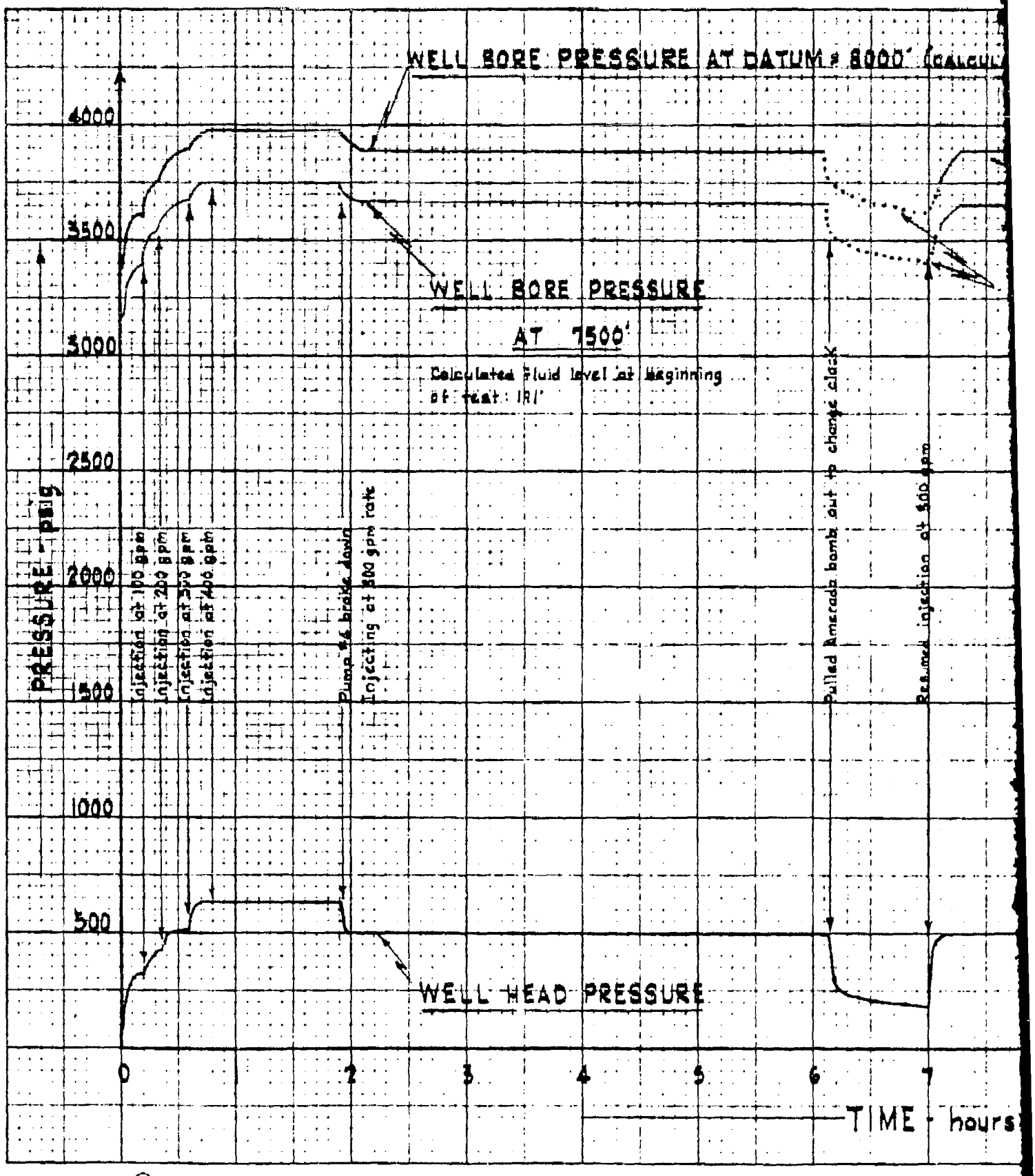

A

FIGURE 9




Columbus, Jr. And Associates, Inc.

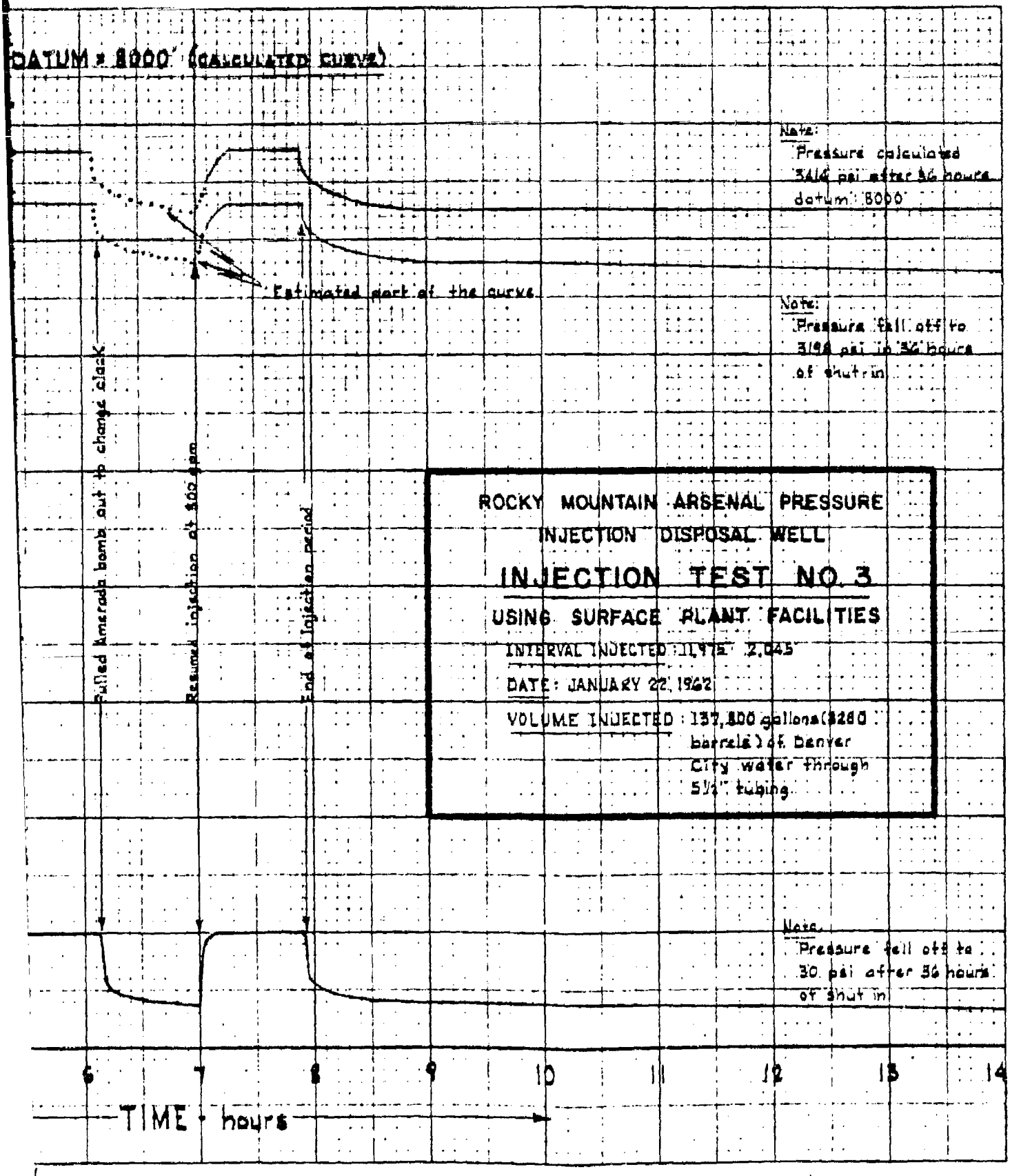
B




A

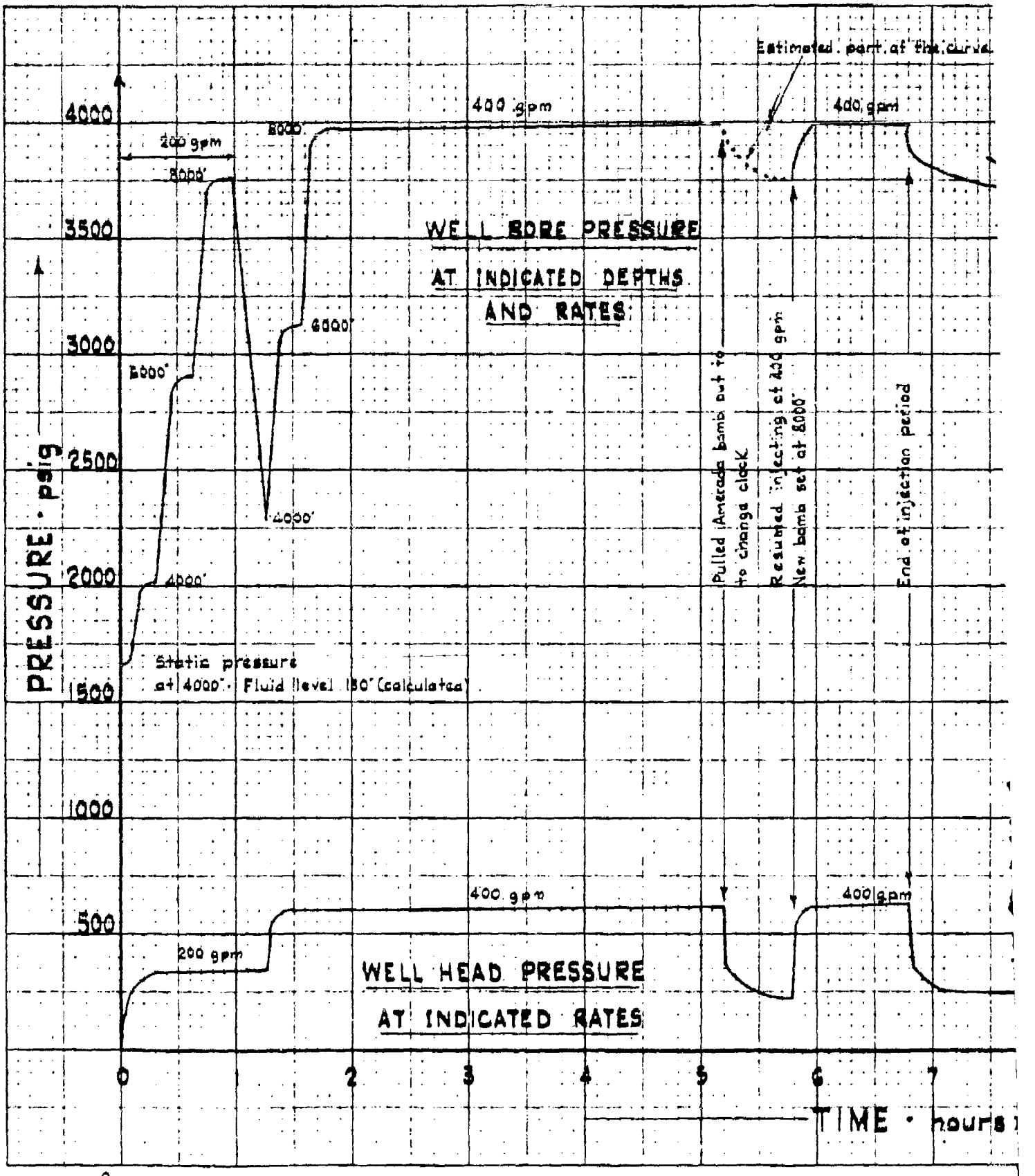
E A Polumbus, Jr And Associate

FIGURE 10




E. A. Polumbus, Jr. And Associates, Inc.

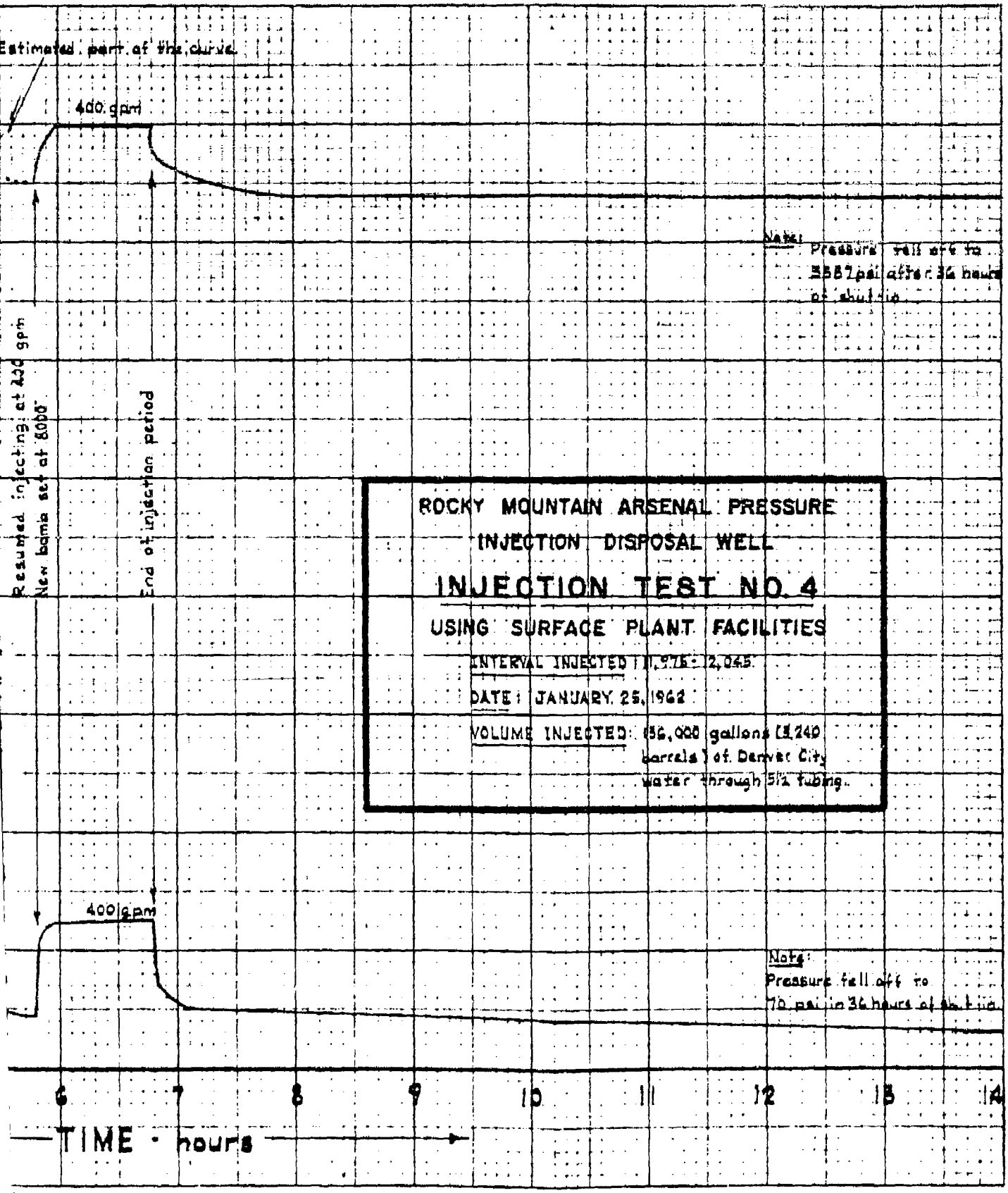
B




A

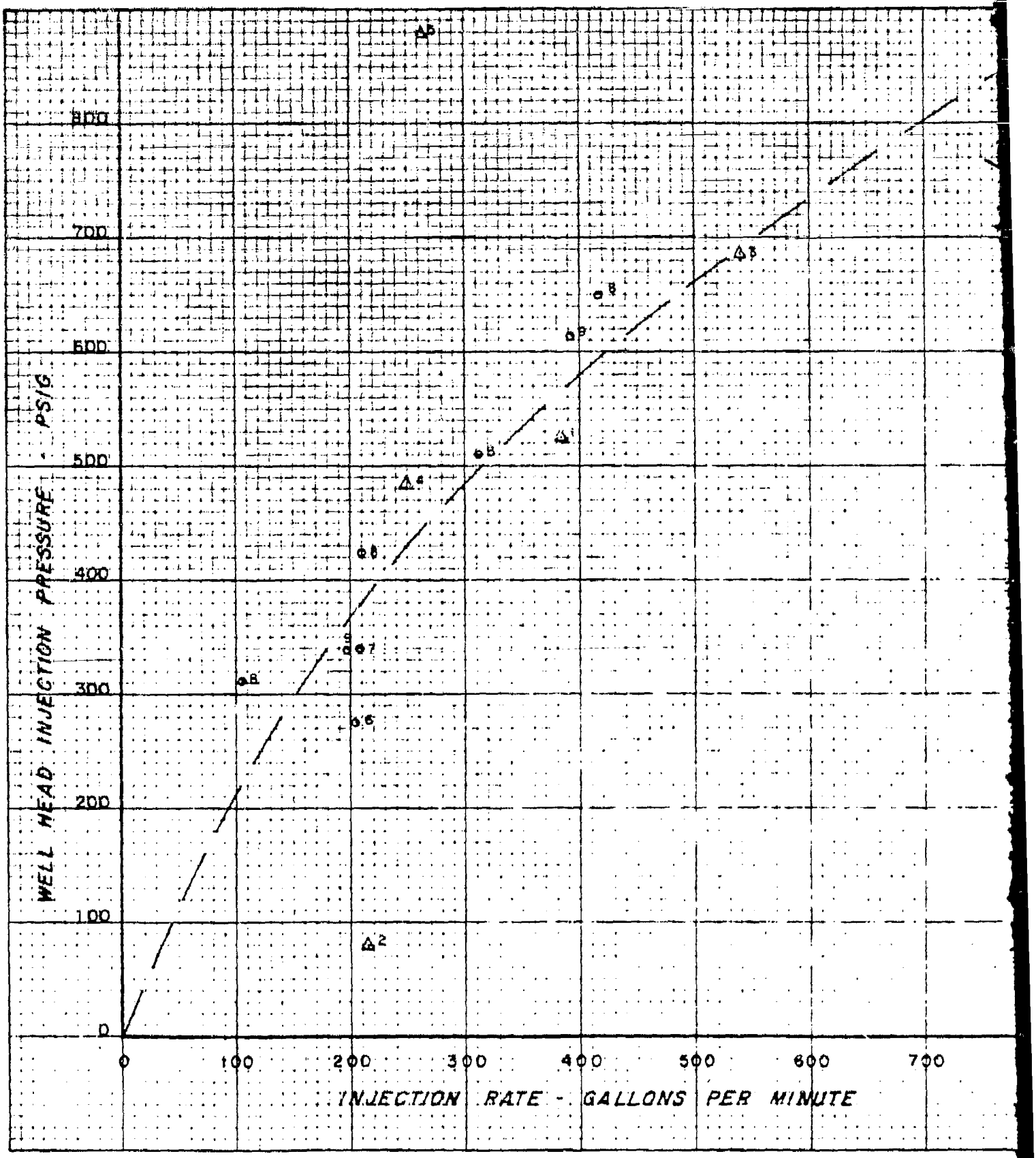
E A Polumbus, Jr And Associates,

FIGURE 11




Columbus, Jr And Associates, Inc

B




A

FIGURE 12

ROCKY MOUNTAIN ARSENAL
PRESSURE INJECTION DISPOSAL WELL
COMPOSITE GRAPH
INJECTION RATES VS. PRESSURES
PRE-CAMBRIAN INTERVAL 11,975-12,048

LEGEND

| Identification | Injection Test No. | Corresponding Figure No. in Report | Injection String | Net Cumulative Injected Volume (Bbls) |
|---|---|---|---|---|
| △1 | 1 | 5 | 4 1/2" dp* | 1835 |
| △2 | 2 | 5 | " | 1660 |
| △3 | 3 | 5 | " | 1800 |
| △4 | 4 | 6 | " | 2352 |
| △5 | 5 | 6 | " | 3926 |
| ○6 | 1 | 8 | 5 1/2" Tubing | 3132 |
| ○7 | 2 | 9 | " | 6180 |
| ○8 | 3 | 10 | " | 9630 |
| ○9 | 4 | 11 | " | 12,870 |

NOTE: The irregularity of points △2 and △5 may be related to the inaccuracy of the volume measurements using rig equipment.

* Pressure values converted to equivalent through 5 1/2" Tubing.

600 700 800

MINUTE

COLUMBUS, JR AND ASSOCIATES, INC

B

END

5-16-68